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AN OIL RECOVERY SYSTEM UTILIZING POLYURETHANE FOAM - A FEASIBILITY STUDY

R. A. Cochran, et al

Edison Water Quality Research Laboratory

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by

R. A. Cochran
J. P. Fraser
D. P. Hemphill
J. P. Oxenham
P. R. Scott

Contract #68-01-0067

Project Officer

J. Stephen Dorrler
Edison Water Quality Research Laboratory, NERC
Edison, New Jersey 08817

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ABSTRACT

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This system is based on the use of polyurethane foam, foamed on the job site, as a sorbent for the spilled oil. The foam is recirculated to increase efficiency and to lower unit costs. Equipment needed includes collection booms, an open-mesh chain-link belt for harvesting the oil-soaked sorbent, and a roller-wringer to remove oil and water from the foam. The foam is initially comminuted and distributed onto the water by means of a hay blower (mulcher), and recycled foam is distributed by an open-throat centrifugal blower. Recovered oil and water are transported to shore in large fabric bags for further treatment prior to disposal. Used foam is disposed of by incineration.

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SECTION I

CONCLUSIONS

1. A practical system for recovery of spilled oils of all types in a wide variety of environmental conditions has been developed based on the use of polyurethane foam, foamed on site, comminuted and distributed by a hay blower, recovered by readily available equipment, recycled many times, and disposed by incineration. An entire system for recovery of oil from the open sea in 30-knot winds, 5-foot seas, and 2-knot currents can be mounted on a conventional 150-foot barge. Individual components of the system are modular and may be air transportable. Oil recovery rates up to 9,000 gal./hr are feasible.

2. A polyurethane foam formulation has been developed for removing spilled oil from water. This foam has the following characteristics:

   a. Specific surface-permeability balance which results in rapid sorption of oils of widely varying viscosities. Sorption times of one to two minutes are adequate.

   b. May be foamed and ready for distribution in two to ten minutes at ambient temperatures from 40°F to 120°F and humidities from 20 to 95%.

   c. Easily handled by inexperienced workers.

   d. Exhibited no toxic effects on F. Similis (a small sea water fish) in laboratory tests (Appendix 3).

   e. Remains buoyant in water if not wrung, and permanently buoyant after wringing when oil wet.

   f. Shelf life of the mixed components of six months.

3. Disposal of used foam can be readily accomplished using a simple incinerator, easily constructed in the field from available materials. Water injection is needed to avoid visible smoke. Analysis of flue gases demonstrated no detectable deleterious nitrogen compounds or chlorides from incineration.

4. Comminution of foamed polyurethane buns in preparation for use in oil sorption can be readily accomplished during the initial distribution process by use of a commercially-available hay blower. Addition of simple shredder bars improves the mulching process.

5. Recycling of used foam and redistribution onto the oil slick surface may be accomplished with a hay blower, but with greater attrition of the foam than would result from the use of an open-throat centrifugal blower.

6. Oil spill booms can be deployed to divert the oil and foam to a harvesting unit. Necessary boom length depends on the current velocity or barge speed.

7. An open-mesh continuous belt can be used to harvest oil-soaked sorbent. Flights are needed to lift the foam particles positively. The proposed system will work most efficiently if it advances through the water at a velocity over 1.5 ft/sec (see also "Recovery of Oil-Soaked Absorbents: An Engineering Study Based on Modification of Existing Device", Ocean Engineering Corporation, API Committee for Air and Water Conservation, March, 1972).

8. Removal of oil and water from the oil-soaked sorbent can be effected practically and simply by gravity-loaded rollers operating against a 1/8-inch mesh chain grate continuous belt conveyor system. Efficiency of oil removal increases with the number of rollers in sequence; two appear to be necessary and three may be used. The residual oil remaining in the foam is on the order of three lb/lb of foam.

9. The rate of oil recovery by this system (as is also true of other oil spill recovery systems) depends strongly on oil slick thickness. Therefore, it is desirable to start cleanup operations as rapidly as possible, before the oil has spread excessively. The use of a surface collecting agent (surface tension modifier) is desirable to limit the spreading of the oil.

10. Unit costs for recovery of spilled oil under the design conditions (9,000 gal./hr, 0.06 in. (1.5 mm) thick oil layer, 30 mph wind, 5-foot waves, 2-knot currents) are estimated to be about $0.15 per gallon of oil recovered, for a large spill. Processing of oil and water and disposal of used foam will result in additional costs.

11. The effluent water contains a significant quantity of oil and will need further treatment before disposal. The most practical system for handling of both oil and water appears to be temporary storage in flexible bags or in bolted tanks on the work barge, with subsequent transport to a land site for processing and treatment.

SECTION II

RECOMMENDATIONS

1. Construction and testing of the proposed oil spill recovery system based on polyurethane foam is recommended.

2. Means of separating oil from the effluent water onboard the work barge should be developed which would allow direct disposal of the effluent water over the side.

3. Further studies of polyurethane formulations are encouraged in order to develop foams which:

   a. Are preferentially oil wettable

   b. Are positively buoyant under all conditions after wringing (oil wet or water wet)

   c. Are resistant to mechanical degradation by the recycling and wringing apparatus

   d. Consist of components with extended shelf lives.

4. Further studies are needed to investigate the effects of emulsions on sorption rates and capacities and overall system performance.

5. Means of reducing residual oil left on the water surface need to be explored. One means which warrants further study is the use of surface collecting agents to maintain a relatively constant oil layer thickness adjacent to the pieces of sorbent.

6. Studies are needed to adapt the system for use on smaller vessels and for smaller spills including a modular system specifically for use in harbors.

7. Means of reducing attrition of the sorbent particles during recycling should be investigated. These should include:

   a. Alternate means of distributing the sorbent after initial comminution. Such systems might take the form of open throat blowers, air stream eductors, or mechanical conveyors.

   b. Changes in wringer design. Reduced wringing pressure and the use of two opposing belts with gradually decreasing inter-belt gap are suggested alternatives (see "Development and Preliminary Design of a Sorbent-Oil Recovery System", Hydronautics, Incorporated; EPA, September, 1972).

   c. Use of higher-strength foam of satisfactory sorption properties.

8. Additional development of subsystem components is needed, not only engineering design (e.g., of conveyor belts) but also further experimental studies of continuous foam generation are desirable.

9. Additional studies of the effects of wind and waves on operational efficiency of the system as affected by vessel size and shape should be conducted.

SECTION III

INTRODUCTION

Concept of System

Spilled oil can be recovered from water by use of sorbents which immobilize the oil so that it can be mechanically harvested. An oil spill recovery system based on the use of sorbents would be usable in a wide variety of environmental conditions, because it is compliant. Rather than resist winds, waves, and currents, the system would move readily under their influence. Further, an oil spill recovery system based on sorbents would be capable of handling a wide variety of oil types and spill sizes.

A wide variety of sorbent materials have been used for collection of oil, ranging from native sponges to hay and straw, wood chips, rice hulls, and expanded vermiculite. All materials used to date have limitations, but the most severe limitation has usually been low efficiency, that is, low weight of oil sorbed per unit weight of sorbent.

It has been shown by many investigators (References 1 and 2) that the efficiency of an oil spill sorbent is inversely related to its bulk density; and the most efficient sorbent yet studied is low density, flexible, open-celled polyurethane foam. Polyurethane foam is sufficiently effective as an oil spill sorbent that its material cost/effectiveness ratio is comparable to that of straw or hay. Earlier studies had indicated that transportation of this material to the job site posed serious logistic problems; however, liquid ingredients may be transported to the job site, mixed, and the polyurethane foamed on location, mitigating the logistics problems associated with handling large volumes of low density sorbents. Thus polyurethane foam, produced on-site, was chosen in the present study as the basis of an oil spill recovery system.

Other components of a complete system for oil-spill recovery based on use of a polyurethane foam sorbent include means for distributing particles of foam on the spill, concentrating the oil-soaked sorbent, harvesting the sorbent, removing oil (and water) from the sorbent, and redistributing the foam for another cycle of the recovery process. Final disposal of the used foam is a necessary consideration in the total system.

Thus, our initial concept of an oil-spill recovery system, illustrated in Figure 1, included the following components:

1. Polyurethane foam, foamed on site from a two-part mixture
2. Mixing and foaming equipment
3. Hay blower to break up the cured foam and distribute it
4. Collecting-confining system
5. Harvesting device
6. Wringing or separating equipment
7. Foam disposal unit

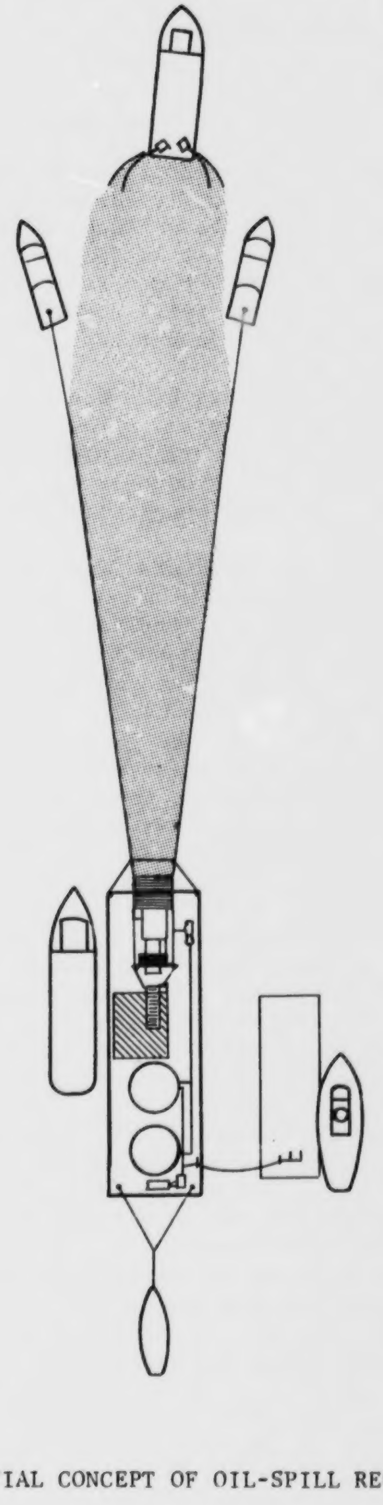

FIGURE 1 - INITIAL CONCEPT OF OIL-SPILL RECOVERY SYSTEM

Other equipment required includes storage vessels for oil and dirty water and a means of separating oil from the water.

Design Goals

The objective in this project has been to develop each subsystem of the initial concept of an oil spill recovery system to provide a firm basis for design of a full scale system. The conditions which this full scale system must meet are outlined in Table 1.

Development of the subsystems is described in Sections VI through XIII and is summarized in Section XIV of this report. Performance of the subsystems is discussed in Section IV. Performance of the total system is discussed in Section V, together with limitations of the system performance which can arise from equipment limitations, from physical limitations (e.g., the rate of sorption of oil from a very thin slick is limited by transport of oil over the water surface), and from environmental constraints.

The experimental facilities used in this study included a wave tank, shown in Figure 2, and a current tank, shown in Figure 3. The wave tank is a fiberglass lined pit, 50 x 125 x 6 feet, equipped to generate waves up to two feet in height with a steepness ratio of 0.1. This tank is equipped for towing tests with a variable speed, double-drum winch on either end of the tank. The current tank can achieve flow velocities of 8 fps through the test section, which is 6 feet deep x 6 feet wide and has one transparent wall for subsurface observation.

TABLE 1

DESIGN GOALS

Source: Contract No. 68-01-0067, Environmental Protection Agency

	Protected Waters	Unprotected Waters
Environment		
Wave heights, ft	2	5
Wind velocity, mph	20	30
Currents, knots	6	2
Recovery System		
Oil recovery capacity, gal./hr	1,350	9,000
Oil properties		
Viscosity	Light diesel to heavy asphalt	Light diesel to Bunker C
Thickness	0.06 in. (1.5 mm)	0.06 in. (1.5 mm)
Oil-Sorbent Separation		
Characteristics of output:		
Oil	< 10% H_2O	< 10% H_2O
Sorbent	Reusable	Reusable
Water	< 1% oil	< 1% oil
Vessel		
Speed, knots at above environmental conditions	12	12
Other	Maneuverable	8 knots speed in 10-foot seas with 38 mph wind
General	Adequate size for equipment and storage needs	
Other Design Goals	Reject floating solids which would interfere with the efficiency of, or damages, the recovery system. Complete removal of oil from the water surface.	

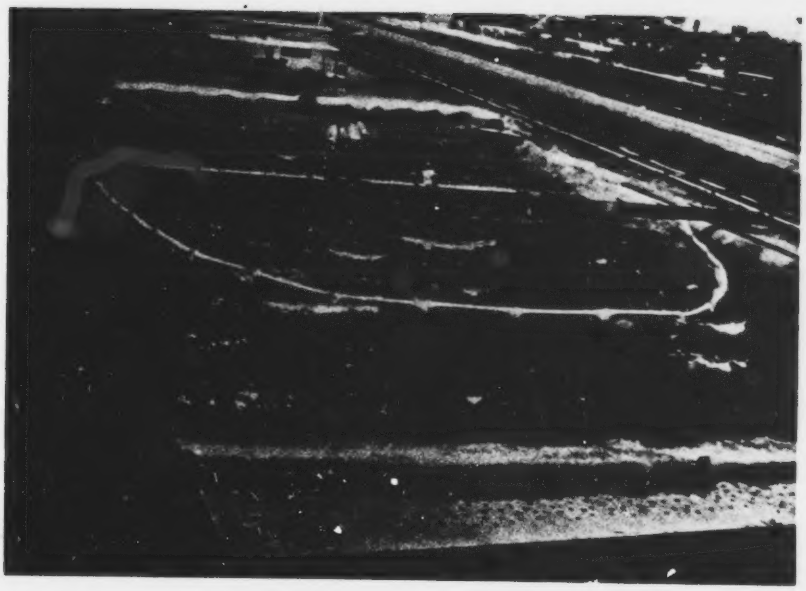

Figure 2 - VIEW OF WAVE TANK

Figure 3 - VIEW OF CURRENT TANK

SECTION IV

PERFORMANCE OF SUBSYSTEMS

Polyurethane Foam

On a weight basis, flexible open-cell polyurethane foam has been found to be one of the most efficient materials for sorbing oil from water surfaces. To minimize the cost of storage and transportation a foam recipe which would allow the fabrication of polyurethane foam at the site of usage was formulated and is shown in Table 2. This two-component recipe produces a foam which is 1) oleophilic, 2) low density, 3) buoyant 4) open cell, 5) flexible, and 6) sorbs oils rapidly relative to the majority of preformed foams readily available. Further, the foam has a pore size distribution which makes it a general-purpose foam which rapidly sorbs and retains large quantities of oils below about 100 cp (centipoise) as well as very viscous oils of 1000 cp (Bunker C). The foam can be reused numerous times with wringing and redistribution systems. The foam components required for this recipe are both non-irritating and easy to handle, requiring only precautions similar to those necessary in handling common, volatile hydrocarbon solvents. Foam produced using this recipe cures rapidly at ambient temperatures from about 40°F to 120°F and relative humidities from about 20% to 95%. The foam is ready for distribution 2 to 10 minutes after mixing. Standard foam equipment capable of pumping and mixing 500 cp to 1000 cp two-component blends at a ratio of 2:1 produce foams having densities from about 1.5 to 3.0 pounds/cubic foot. Under ideal conditions, this foam is capable of sorbing oils equivalent to many times the weight of foam used. The quantity of oil sorbed depends upon many factors, e.g., thickness of oil film, viscosity of oil, degree of agitation, length of exposure time, particle size of foam, areal coverage, etc. Properties and sorption rates typical of this on-site generated polyurethane foam are compared with those of two preformed polyurethane foams used in the furniture industry in Table 3. Sorption values are shown in Table 4.

Distribution

The polyurethane foam must be distributed over the surface of the oil spill at concentrations ranging from 0.04 to 0.1 lb/ft^2 and at as high as 3 lb/gallon of oil. It is anticipated that the maximum distance the foam must be delivered from a vessel will be less than 50 feet. In practice, foam will be placed within containment booms or will be spread upwind since the sail area of each piece causes it to move downwind faster than the oil spill. In tests of a small power mulcher (Reinco Model TM7-30, manufactured by Reinco, Plainfield, New Jersey) it was found that good, controlled distribution could be obtained at distances up to 60 feet in calm air. Against a 7-knot wind, the range was reduced by half. The mulcher discharge may be into a conduit, however, and the foam delivered to a header directly over the water. The entire foam requirement for the protected water system could probably be delivered by two of these mulchers. For the offshore system, four of a larger unit (e.g., Reinco Model M60-F6) would be needed.

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TABLE 2

RECIPE FOR ON-SITE POLYURETHANE FOAM

Component	Parts by Weight in Blend
6500 MW Polymeric triol with a functionality of near three (Polyol)[1]	100
Dichloromethane	10
Water	5
Tertiary amine catalyst[2]	
Polymeric Methylenediphenyldiisocyanate[3] (MDI)	50 - 80

---

1) Thanol® SF6500 made by Jefferson Chemical Company, Incorporated
2) Thancat® TAP made by Jefferson Chemical Company, Incorporated
   Thancat® DD made by Jefferson Chemical Company, Incorporated
3) Papi® made by the Upjohn Company
   Rubinate® M made by Rubicon Chemical Incorporated
   Thanate® P-30 made by Jefferson Chemical Company, Incorporated

Note: The 6500 MW polyol, dichloromethane, water and catalyst are blended to make one component-Component B. Component A consists of (MDI). The ratio of Component A to Component B is not critical. However, usable foams are produced at ratios of 1:1.5 to 1:2.5. The best foam is produced at a ratio of about 1 Component A to 2 Component B.

TABLE 3

COMPARISON OF PHYSICAL PROPERTIES AND SATURATION TIMES FOR FOUR POLYURETHANE FOAMS

Test Condition:

Two-inch cubes of foam were placed on the surface of 77°F test oil contained in two-liter beakers. A stopwatch was started on contact. The percent of foam not wetted with oil was recorded at various time intervals.

Foam Samples Description:

1. On site generated polyurethane foam - Batch made 11/2/71
2. On site generated polyurethane foam - Batch made 12/3/71
3. Commercial polyurethane foam used to make pillows, cushions, etc.
4. Commercial polyurethane foam used to make seat cushions

Properties:	Sample 1	Sample 2	Sample 3	Sample 4
Density, lbs/ft^3	1.74	2.23	1.11	1.44
Tensile strength, lbs/in^2	3.8	3.1	12.0	11.5
Cell openings, No./in.	58	56	100	100
Compressibility, $lbs/50\ in^2$				
25% compression	7	7	17	33
50% compression	12	11	20	45
65% compression	19	18	27	64

Note: Samples 3 and 4 represent the major quantity of readily available foam at foam fabricator usable for absorbing oil.

Test Oil Description:

1. No. 2 Diesel Fuel
2. Blend of No. 2 and Bunker C Fuel
3. Bunker C Fuel

Properties:	No. 2 Diesel	Blend	Bunker C
Gravity °API at 60°F	42.3	24.5	10.8
Viscosity at °F, cs			
60	2.6	27	2700
77[1]	2.2	13	1000
80	2.1	12	890

---

1) Test temperature

TABLE 3 (Continued)

Foam Saturated %v	Test Time, Minutes														
	No. 2 Diesel Fuel					Blend Fuel					Bunker C Fuel				
	Sample 1 (On-Site)	Sample 2 (On-Site)	Sample 3 (Comm'l)	Sample 4 (Comm'l)	Sample 5 (Scott)	Sample 1 (On-Site)	Sample 2 (On-Site)	Sample 3 (Comm'l)	Sample 4 (Comm'l)	Sample 5 (Scott)	Sample 1 (On-Site)	Sample 2 (On-Site)	Sample 3 (Comm'l)	Sample 4 (Comm'l)	Sample 5 (Scott)
5	--	--	0.13	0.3	--	--	--	--	60	--	1.5	--	180	360	--
10	--	--	0.19	--	--	0.07	0.03	25	240	0.05	3.0	3.0	1,200	9,000	2
20	--	--	--	0.6	--	0.13	--	40	--	0.10	7.5	7.5	4,300	18,000	2.5
30	0.04	0.03	--	2.7	--	0.16	0.09	50	--	--	13.0	13.0	9,000	--	5
40	--	--	--	20	--	--	--	55	--	0.15	21.5	20.0	18,000	--	8
50	0.06	0.07	0.50	120	0.20	0.25	0.16	65	1300	0.25	27.5	27.0	--	--	11
60	--	--	--	1300	--	--	0.23	90	--	--	30.0	31.5	--	--	--
70	--	--	1.0	5000	--	0.33	0.31	110	--	0.33	33.5	41.5	--	--	20
80	0.10	0.13	--	--	--	0.43	0.25	--	4300	0.40	42.0	45.0	--	--	26
90	--	--	--	9000	--	0.50	0.55	--	--	--	49.5	50.5	--	--	--
95	--	--	--	--	--	0.60	--	270	--	--	54.0	55.0	--	--	--
99	--	--	--	17,000	--	--	--	--	--	--	63.5	--	--	--	-
100	0.13	0.19	49.0	--	0.06	0.93	0.70	315	7200	0.70	68.0	67.0	--	--	39

TABLE 4

COMPARISON OF MAXIMUM OIL SORPTION DATA FOR TWO POLYURETHANE FOAMS

Experimental procedures are described in Table 3.

Drain Time	Oil Held by Material lb Oil/lb Material	
	Commercial Foam	On-Site Generated Foam
	No. 6 Fuel Oil Sp Gr = 0.996	
5 min	53.6	29.9
15 min	51.2	29.2
30 min	50.6	28.8
1 hr	47.0	28.2
2 hr	45.3	28.0
	Shallow Yates Crude Oil Sp Gr = 0.905	
5 min	36.3	22.9
15 min	35.4	22.1
30 min	34.6	22.0
1 hr	34.1	21.8
2 hr	33.7	21.5

Foam Description:

1. Commercial Foam TDI - Polyether
2. On-Site Generated Foam MDI - Polyol

Properties:	1	2
Density, lb/ft^3	1.1	2.3
Pores per inch	100	60

Power mulchers are readily available for emergency mobilization (Reinco has listed several hundred that are in use throughout the Midwestern and Eastern parts of the United States) and can be modified quickly at the job site. Recommended modifications before use for mulching and initially distributing the buns consist of the addition of several studs in the beater chamber wall to control the foam particle size and the provision of an extended charging chute as an aid in increasing the throughput (especially for foam which has been pre-mulched or is being recycled). An alternate means for distributing the foam during recycling (open throat blower, air stream eductor, or mechanical conveyor) should be considered to reduce further attrition of the sorbent particles after the initial mulching.

Collecting

The foam will be distributed within or directly before the mouth of a channel formed between two converging booms or one boom and the barge upon which the processing equipment is located. The required boom angle to the current will be very shallow (i.e., much less than 30°) and foam containment should be effective up to a velocity of at least three ft/sec. From experiments, continuous flow of the oil-soaked sorbent through this channel should be realized despite high areal concentration of the sorbent. The sorbent will then flow through the confined channel, as indicated in the photograph of the test booms shown in Figure 4,

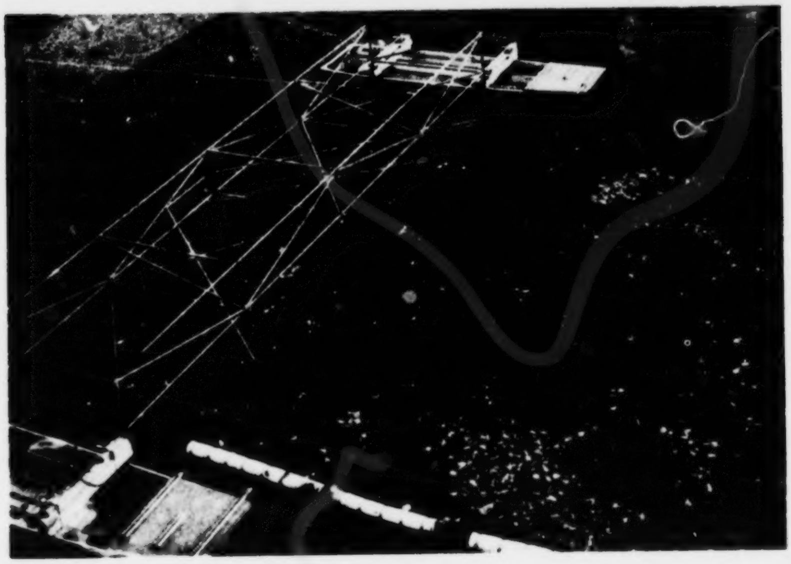


Figure 4 - TEST BOOM ASSEMBLY IN WAVE TANK

to an inclined wire mesh belt harvesting apparatus where it will be lifted from the water onboard the barge. The experimental harvesting apparatus is shown in Figure 5.

The tow tension in each boom should be taken up at several points along its length to allow it to conform to the water surface, minimizing splash-over and broaching of the booms between wave crests. Sharp corners on floats or at boom ends and steep inclinations of the boom to the current should be avoided to minimize wash under of the sorbent. A properly designed system with an included angle of 30° or less, a freeboard of two feet and a draft of one foot should be effective to velocities of three ft/sec if the booms are sufficiently flexible to conform to the waves.

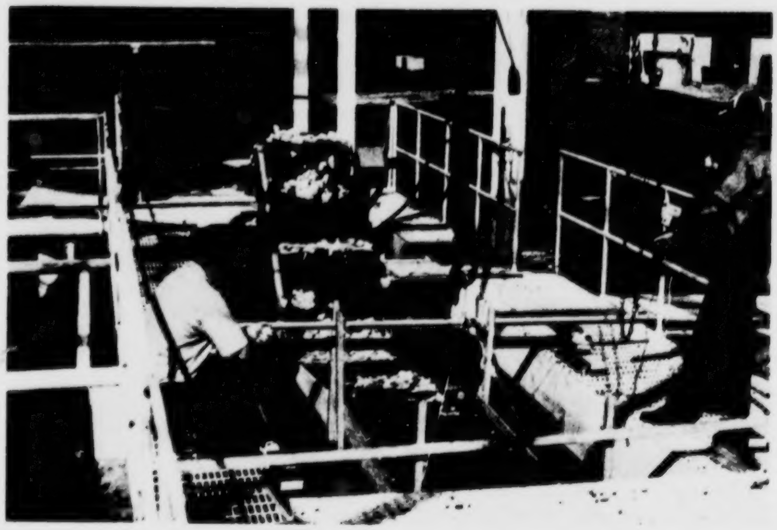
Wringing

The wringing experiments described in Section XI demonstrate a simple wringer concept to be capable of removing a satisfactory amount of oil at conveyor speeds approaching 100 ft/min and at imposed wringer pressures from 7 to 30 lb/in. of wringer width using simple pipe rollers. These experiments also demonstrate that there is a residual amount of oil remaining in the foam after extensive wringing which must be recycled with the foam. The ratio of the weight of the residual oil to that of the dry foam varied from three to six, the largest values being for the most viscous oils. Some foam attrition was observed for the highest viscosity oils tested, but even with 1100 cs oil only 2% to 3% foam per cycle is reduced to a size smaller than that which will pass through a one-inch mesh by the wringing process along.

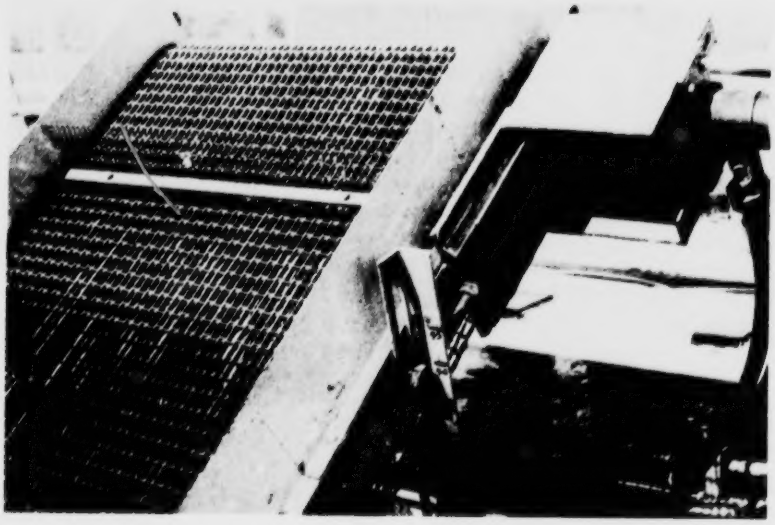
The oil removal system proposed consists of two sets of gravity-loaded pipe rollers through which the foam is successively wrung. Foam would be carried to and through each set of rollers on a wire mesh belt conveyor as shown in Figure 6. Sufficient wringing pressure can be obtained by making the top rollers of 24-inch diameter pipe with 1/2-inch wall thickness filled with water. The heavy top rollers can be left free to move vertically within guide bars rather than constrained to operate at a constant gap. In this way the wringer is flexible and can accommodate mulched foam layers of varying thickness as well as debris which the harvester may pick up. Experiments with this design have shown that satisfactory oil removal can be obtained with layers of mulched foam up to six inches deep wrung at a speed of 70 ft/min.

Foam Disposal

Generally, it is necessary to dispose of the polyurethane foam after it has been used to sorb spilled oil. Techniques which might be used without creating additional pollution problems were considered. Disposal methods which were investigated included solution, compaction, and burning. Burning appears to be the most rapid and practical method of disposing of used foam. To accomplish this a furnace to burn used foam without producing appreciable quantities of particulate emissions was



(a)



(b)

Figure 5 - MODEL HARVESTER INSTALLED IN CURRENT TANK

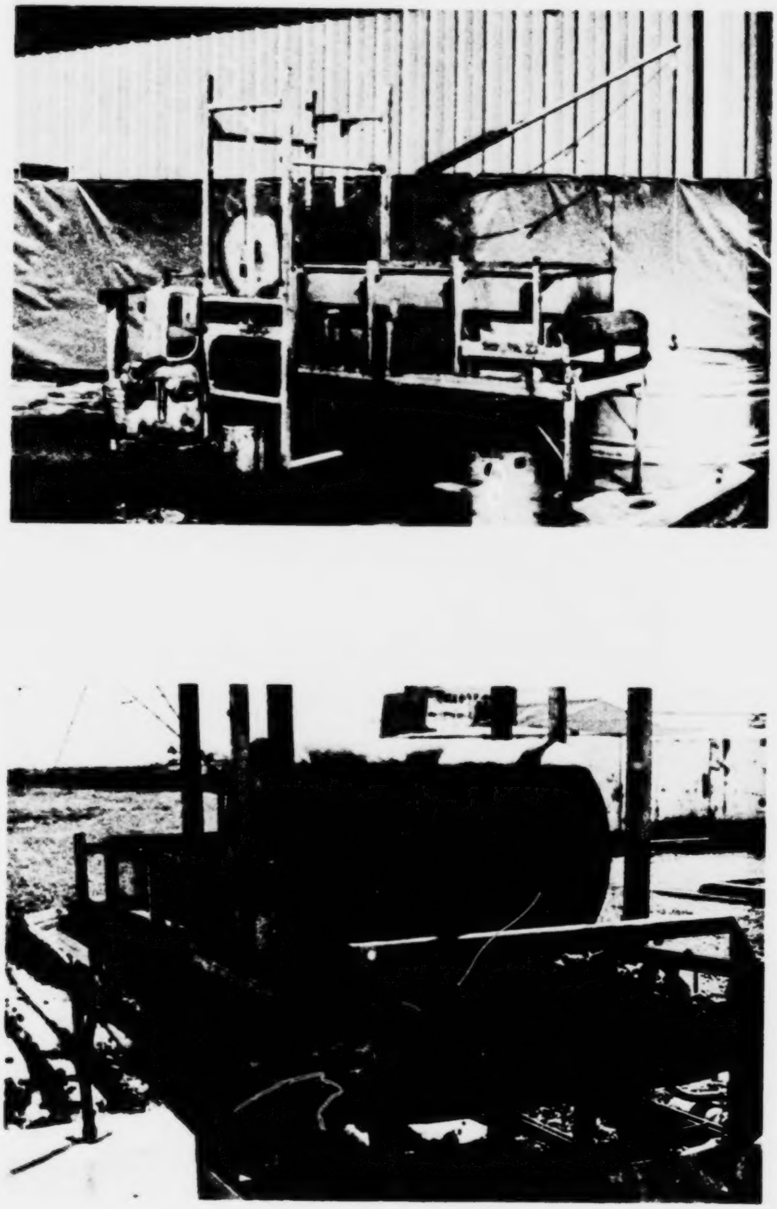


Figure 6 - EXPERIMENTAL WRINGING APPARATUS

built and operated. The model furnace is shown in Figure 7. Burning rates are presented in Table 5.

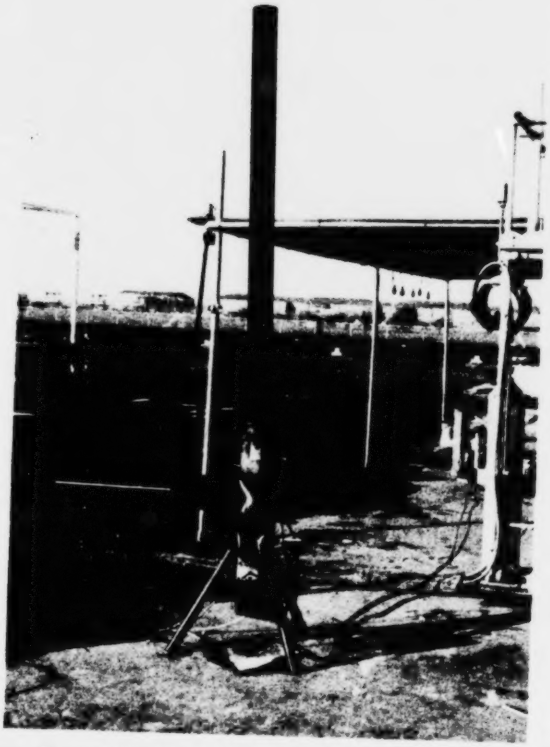


Figure 7 - SHELL PIPE LINE MODEL FURNACE USED TO BURN POLYURETHANE FOAM

Burning tests in the 6.25-inch diameter model furnace indicate:

1. Polyurethane foam used to sorb Bunker C and No. 2 Diesel fuels from water can be burned at rates from 10 to 20 pounds per hour per square foot of grate area (on the basis of dry foam) without producing smoke.
2. The burning rate for dry, unused foam is about 40 pounds per hour per square foot of grate area.
3. Water, either added while burning foam or absorbed while sorbing oil from water, greatly reduces the particulate emissions. When

TABLE 5

POLYURETHANE FOAM BURNING RATE FROM FURNACE MODEL

Description of Foam	Burning Rate, Pounds of Dry Foam per Hour per Square Foot of Grate Area	Flame Temperature ^oF	Stack Temperature ^oF	Auxiliary Fuel Consumption SCF/Hr	Unburned Foam or Oil Lost as Dripping %w
Dry	36	1400-1500	1400-1500	42	Nil
Water Wet	14	1300-1400	1300-1400	42	Nil
No. 2 Diesel Wet	9	1400-1500	1400-1500	42	Nil
No. 2 Diesel Water Wet	15	1300-1400	1300-1400	42	Nil
Bunker C Water Wet	8	1200-1400	1200-1500	68	6
Bunker C, No. 2 Diesel Mix - Water Wet	14	1400-1500	1400-1600	68	1.5

either dry foam or oil-soaked foam is to be burned, water should be sprayed on the foam prior to burning. The quantity or rate can be established by trial.

4. No deleterious nitrogen compounds or chlorides were detected by an analysis of flue gases evolved during foam incineration, as indicated in Table 6.

5. Additional fuel is required to fire an igniter and an afterburner.

6. A furnace to burn used polyurethane foam can be constructed in the field utilizing readily-available materials and manpower.

TABLE 6

FLUE GAS ANALYSIS OF EVOLVED GASES WHILE BURNING FOAM CONTAINING NO. 2 DIESEL FUEL

Component	Volume, %
Carbon dioxide	5.0
Argon	1.0
Hydrogen sulfide	0.0
Oxygen	14.2
Carbon Monoxide	0.0
Nitrogen	79.3
Hydrogen	0.08
Helium	0.0
Methane	0.08
Ethane and heavier hydrogens	0.04
Acetylene	0.06
Water	0.02

Note: No cyanides, isocyanates, or chlorides were detected in the flue gas.

SECTION V

SYSTEM PERFORMANCE

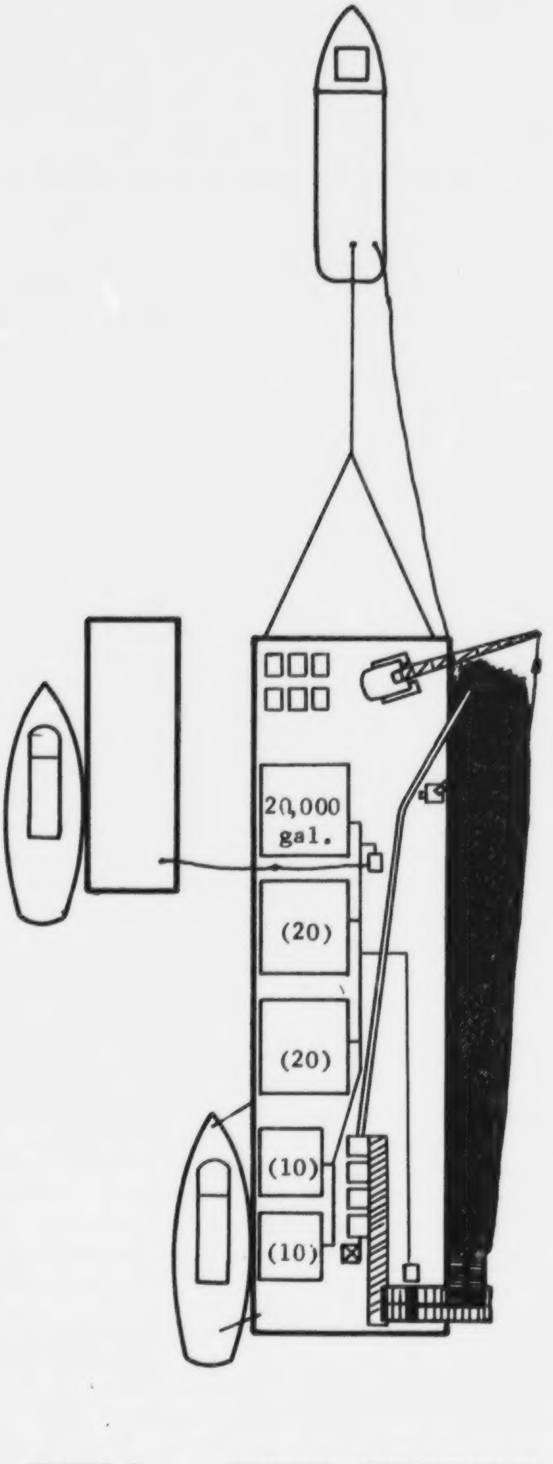
Prototype Design

The oil recovery system now proposed is fundamentally the same as the original concept of Figure 1. This study has increased our understanding of the processes involved and led to refinements in certain parts of the system. The most obvious and significant changes have been the reduction in size of the boom array needed and the use of a redistribution system other than the mulcher-blower to reduce attrition during recycling. The reduction in boom length has made it practical to consolidate the system into a configuration which may be placed on a single large flat-deck barge, or, with benefit of the modular design concept, deployed as dual systems aboard smaller barges or work boats (see Figures 8 and 9). It should be emphasized that consistent effort to remain conservative in extrapolations from laboratory to prototype has doubtless resulted in a system having a greater capability than specified.

As shown in Figures 8 and 9, the foam is placed only within the area confined by a boom, and little or no loss of foam to the sea is to be expected. Any floating debris which may pass through the boom throat will be accepted by the harvester. Sufficient time is provided in transit on the harvester and wringer feed conveyor for inspection and for manual removal of debris. Small debris will not damage any part of the system except, possibly, the blower. The quantity of water contaminate recovered with the oil is strongly a function of slick depth and oil properties. To assure consistent attainment of the design goals for effluent purities, recovered liquids are treated at oil-water separation facilities on shore, where the operation is efficient and the effluent can be well controlled (see page 137). With a battery of storage containers manifolded on board, however, it may be desirable to segregate the oil-rich wringing effluent from the generally oil-free water drained prior to wringing.

Vessel motions are not expected to restrict operations to any great extent within the range of sea conditions specified. The recovery vessel is generally expected to operate approximately parallel to the direction in which the oil spill is moving and thus be working into the wind and waves. The pitch and heave motions under these conditions should not affect the system or the personnel. Consideration must be given to the proper securing of the liquid storage tanks, however, since large inertial forces will be generated by vessel motion when the containers are in use.

As large barges of the type preferred are available for charter in most major shipping areas, but not in all potential oil spill areas, all components



20,000 gal.
(20)
(20)
(10)
(10)

FIGURE 8 - PROPOSED CONFIGURATION

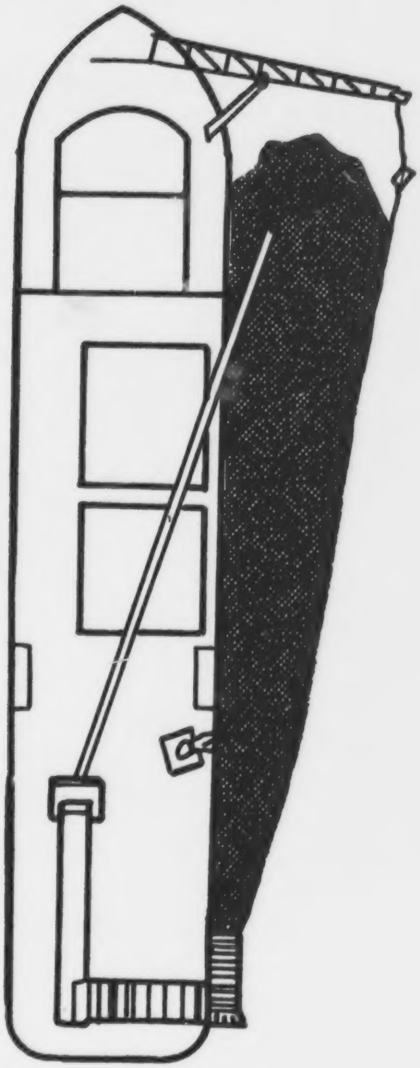


FIGURE 9 - USE OF COMPONENT MODULES FOR REDUCED CAPACITY SYSTEM

of the system are modular and may be employed in various combinations to suit the availability of vessels. Two half-size systems can be assembled on work boats, small barges, etc. without modification to the equipment itself. The only component of this system that would require disassembly before truck shipment is the recycling conveyor, and this can be designed for quick assembly from palletized packages (and could be stored in that fashion, even on a barge). In practice the entire system could be maintained for immediate loading on trucks or aircraft similar to the C-130.

The cost of oil recovery using this polyurethane foam based system including the transportation of recovered effluents and used foam to shore is estimated to be on the order of $0.15 per gallon of recovered oil, as shown in Table 7. The cost of operating shore-based treatment and disposal facilities will increase this cost somewhat.

TABLE 7

ESTIMATED COST OF OIL RECOVERY USING POLYURETHANE FOAM

Basic Costs

1 - 200' Barge	$ 650/day
1 - 1,000 hp Tug	900
30 man-days labor/day at $7.50/hr	5,400
Basic System	$7,670/day

$$\frac{\$7,670}{\text{day}} \times \frac{\text{hr}}{9,000\ \text{gal. oil}} \times \frac{\text{day}}{24\ \text{hr}} = \$0.036/\text{gal. oil}$$

Support Vessels

3 - 600 hp Tugs at $30/hr	$2,160
3 - Cargo Barges ~ 140'±	1,200±
2 - Crew Boats	600±
	$3,960/day = $0.018/gal. oil

Material (Sorbent) Costs $= \dfrac{(1\ \text{gal.})\cdot(7.5\ \text{lb/gal.})\cdot(0.10)\cdot(\$0.37/\text{lb})}{3\ \text{lb/lb}} =$ $0.092/gal. oil

(Assumes 10% loss/pass and 3 lb/lb oil sorption — See Section XII and Appendix 2)

Total $0.146/gal. oil

Limitations of System

Limitations to performance of this oil spill recovery system can arise from environmental conditions, physical limitations inherent in the oil/water/sorbent system, and limitations in the equipment items needed.

The rate of transport of oil on water to a sorbent particle and the rate of sorption of oil by a given sorbent particle depend on the oil layer thickness. Therefore, the overall rate of oil recovery by the system will decrease with thickness of the oil layer as is true with most recovery systems. High oil viscosities will result in a slower rate of transport of the oil on the water surface and a slower rate of migration of oil into the foam particles. This may be partially compensated by increased retention of adsorbed oil on the outside of the foam particles with increased viscosity (see page 62).

A sorbent-based oil spill recovery system may be less sensitive to the effects of wind, waves, and currents than mechanical systems, because the sorbent-based system is generally compliant. Nevertheless, adverse environmental conditions will affect performance. In addition to problems of ship and boat handling and problems of operating on the deck of a moving vessel, the following limitations are expected:

a. Wind will affect the ability to distribute foam uniformly and will affect the distance over which it can be projected by a blower without significant losses. Further, wind will tend to move the foam over the water surface until it absorbs oil and water so as to sink partially, decreasing the freeboard upon which the wind may act and increasing the draft and drag of the particles. These effects of wind can be minimized by use of a distribution manifold cantilevered from the bow of the work barge over the area on which foam is to be dispensed.

b. Waves may increase the efficiency of the sorbent and the performance of the harvester. However, the harvester design should be such that the lower end will not broach out of the water and the booms used to divert oil-soaked sorbent to the harvester should be relatively insensitive to waves.

c. Rain will probably interfere with the foaming operation, although this can be controlled by use of shelters.

d. Temperature will affect the foaming reaction, although our studies indicate that the selected formulation is usable over a wide range (at least from 40° to 120°F). At low temperatures, it may be desirable to heat the foam components prior to mixing in order to speed up the foaming reaction.

e. Currents pose significant operating problems for boom systems. Failure of booms to contain oil and sorbents and mechanical breakage may occur at high current velocities. A major concern for the proposed recovery system at high currents is to provide enough contact time between the foam and the oil. It should be noted that there is a relative velocity below which the wet sorbent will be kept away from the harvester by circulation patterns produced by motion of the harvester belt (see page 106).

A primary limitation on the performance of this system arises from the loss of foam due to attrition (see Section XII). There are two primary sources of attrition, the foam transport system and the wringer. If the Reinco hay blower is used both for preparation of the foam (comminution) and foam transport, significant generation of fine particles is likely with each cycle. This attrition can be minimized by use of two separate systems, one for foam comminution (the hay blower), and an open-throat centrifugal blower or mechanical conveyor for foam transport during recycling.

Attrition during wringing is especially severe for the more viscous oils, over 100 centistokes (cs), owing to high internal pressures generated within the foam as the oil is forced out. The pressure generated is a function of the oil viscosity and the rate of oil removal; this suggests that a modified wringer configuration (two opposing open-mesh belt, with gradually reducing gap between them, as suggested by Hydronautics, Inc., see page 3) could be used to minimize this source of attrition.

Sinking of the foam is not expected to be a severe problem, because foam which has become oil-wet will apparently remain permanently buoyant. Minor losses of foam can be expected from sinking of foam which has been exposed to water only, wrung out, and then redistributed onto the water surface (see page 31).

SECTION VI

FOAM FABRICATION AND CHARACTERISTICS

Introduction

To minimize the cost of storage and transportation it is desirable to fabricate polyurethane foam at the site at which it will be used. The foam should have the following properties:

1. Oleophilic
2. Low density
3. Positive buoyancy
4. Open cell
5. Flexibility
6. Rapid cure under a wide variety of conditions
7. Require simple and rugged equipment to produce, disperse, and harvest
8. Be easy and non-hazardous to produce

A polyurethane foam possessing these properties has been developed.

On-Site Foam Formulation

Components in the recipe described in Table 2 are both non-irritating and easy to handle, requiring only precautions similar to those which should be taken when handling common volatile hydrocarbon solvents. This formulation cures rapidly at any ambient temperature between 40°F and 120°F and relative humidities between about 20 and 95%. The foam is ready for distribution two to ten minutes after mixing and has a density between 1.5 and 3 lb/cu ft. This foam can be made and distributed at the site of an oil spill.

The reactions involved are described in Appendix No. 1. About two hundred blends utilizing these and other components were made and tested. One formulation was consistently preferred. Details concerning a part of the formula testing are described in Appendix No. 2.

Foam Properties

The properties of individual batches of foam vary depending upon a) climatic conditions, b) mixing conditions, and c) component ratio (Table 8); however, no batch of foam has been produced, using recipe in Table 2, which was unsatisfactory for absorbing oil from water. The density of the foam is the property most influenced by the above variables; it varied between 1.7 lb/ft^3 and 2.7 lb/ft^3. The rise time and cure time to tack-free increased as the temperature decreased. Foam having a density of about 2.1 lb/ft^3 is typical. Properties of this foam are shown in Table 8. Pore size and distribution are indicated by the foam cross-section shown in Figure 10.

TABLE 8

FOAM PRODUCTION RATES AND FOAM PROPERTIES

Conditions: Polyurethane foam produced from recipe shown in Table 2 using the following equipment:

Graco Hydracat Variable Pumping Unit

Consists of President Model 205-038 Series D Air Motor which drives two Graco Size 2 displacement pumps mounted on a portable frame, with associated filters and hoses.

Binks 18 FM gun with flush equipment consisting of a 5-gallon Monark Hydra Spray unit, Model 226-153 Series "A".

Foam applied to kraft paper to form bun about 18 inches wide.

Components were near ambient temperature except for December 3 production. In this case components were near 70°F.

Date:	Nov. 2, 1971	Nov. 29, 1971	Dec. 3, 1971	Jan. 11, 1972	June 21, 1972
Ambient Temperature, °F	90	60	40	45	--
Relative Humidity	--	--	--	80	--
Pour Rate, lb/hr	307	360	330	--	--
Density, lb/ft^3	1.7	2.2	2.2	2.1	2.15
Tensile Strength, lb/in^2	4	3	3	3.1	3.2
Pores Per Inch	58	60	56	60	47
Compressibility, lb/50 in^2					
25% Compressed	8	7	7	15	5.5
50% Compressed	13	10	11	27	8.4
65% Compressed	21	14	18	44	13.6

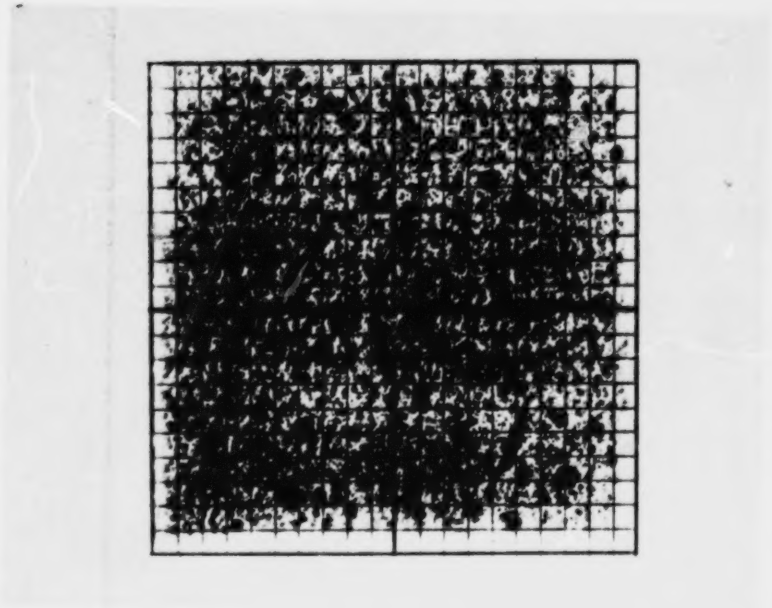


Figure 10 - TYPICAL ON-SITE GENERATED POLYURETHANE FOAM PRODUCED AT 45°F AND 80% RELATIVE HUMIDITY JANUARY 11, 1972 (2 X 2 INCH GRIDE WITH SUBDIVISIONS OF 0.1 INCH)

The foam described in Table 8 and Figure 10 was given to the Edna Wood Laboratories, Houston, Texas for a bioassay. Foam was added to test tanks in quantities equivalent to 0.01, 0.11, 0.60, 1.1, and 2.2 inch thick layers of foam on 3-foot deep water. Killifish (Fundulus Similis, a sea-water species) in the test tanks were exposed to the foam for 96 hours. At the end of the test period all fish were normal. Details concerning these tests are shown in Appendix No. 2.

Tests were undertaken to determine the persistance of the foam buoyancy. Typical data for the sinking of dry foam into quiescent sea water are shown in Figure 11. Foam which has been oil wetted by application to an oil slick on water does not sink after subsequent wringing and reuse cycles.

Dry foam mulched by a modified Reinco hay blower (Model TM 7-30) was soaked in water and then passed through our model wringer. Upon returning the foam to the water, 2% sank. After a second wringing cycle, an additional 5% sank. In four subsequent cycles no more foam sank. A thin oil slick was added to the water surface. The water-wet foam, including that portion which had sunk earlier, was applied to the oil slick. All foam remained afloat. The foam was then passed through four cycles of wringing and

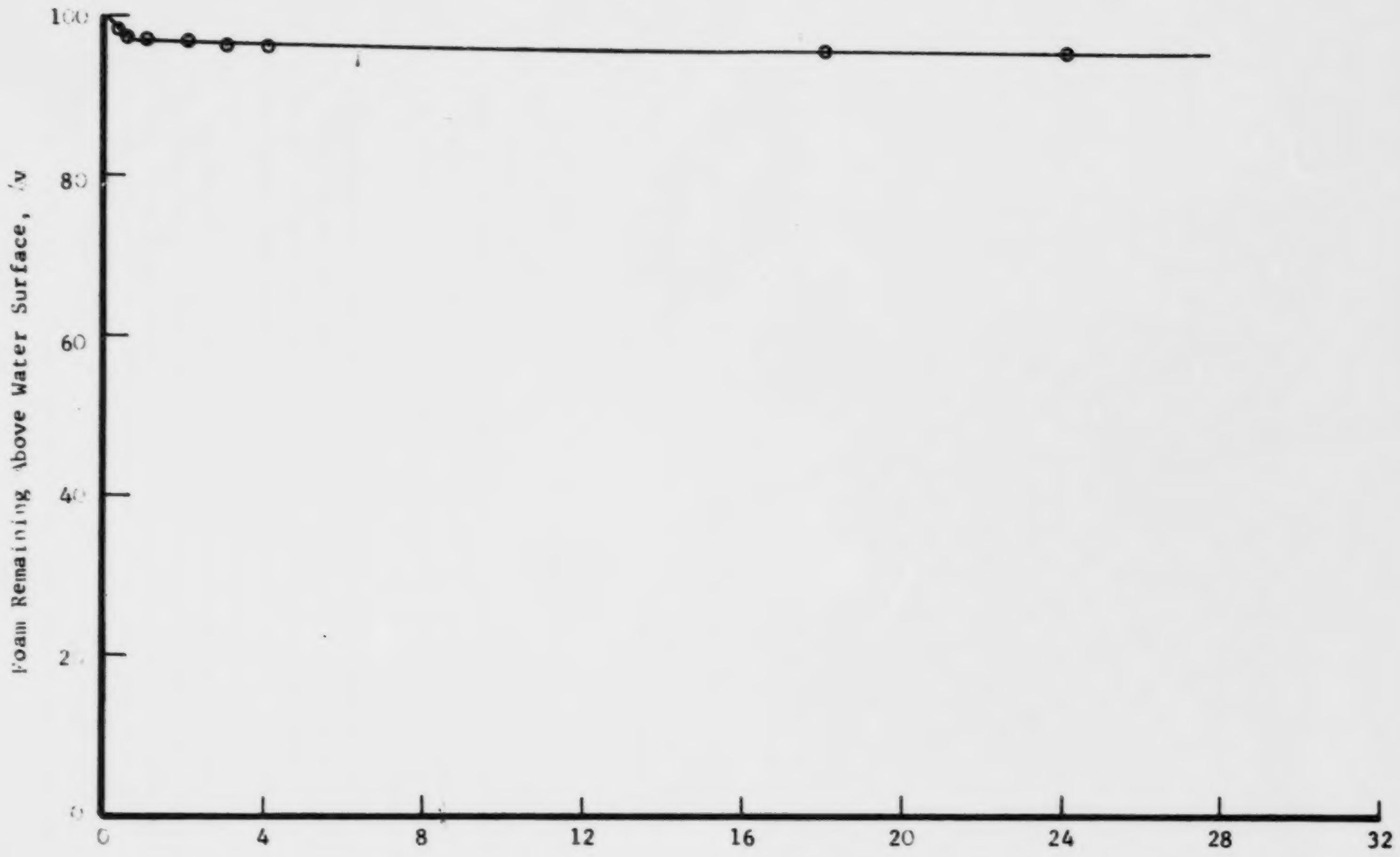


FIGURE 11 - SINKING RATE OF ON-SITE GENERATED POLYURETHANE FOAM INTO QUIESCENT SYNTHETIC SEA WATER

reapplication to water only (no oil slick). The foam was then left on the water for 138 hours with no loss due to sinking. These experiments demonstrate that fully dry foam and foam that has had some exposure to oil will not sink. Those foam particles which did sink when fully saturated with water had no surface "skin". Evidently the "skin", which is a result of the interaction between the exterior foam surface and the air when the foam is made, provides a sufficient number of closed cells to prevent sinking.

Test data presented in Table 3 show that on-site generated foam absorbed oils more rapidly than typical commercially-available foam such as used in the furniture industry. This is due in part to the larger pores and consequent higher permeability of on-site foam. These data also show that on-site foam absorbed No. 2 Diesel Fuel about 450 times more rapidly than Bunker C Fuel which was about 450 times more viscous at test conditions. When on-site foam was held stationary in both No. 6 Fuel oil and Shallow Yates crude oil, capillary forces saturated the foam to a height of 0.25 ± 0.03 inches above the level of the oil.

Data in Table 4 show that, once saturated, the commercial foam contained and retained more oil than on-site foam. The difference between the bulk densities of the two foams is the most likely explanation for the difference in sorption capabilities.

During tests made to determine the ability of the foam to remove thin oil slicks from water, it was noted that foam placed on a thin slick removed the oil in the immediate area. The absorption rate then tended to exceed the gravitational flow transfer of oil from the surrounding slick to the foam. In some cases the oil would not approach the foam, leaving it in an area free of oil. (This was also observed to happen when samples of furniture-industry foams were placed on a similar thin slick). This tended to decrease the oil-to-water ratio in the total liquid sorbed and to decrease the oil-sorbed-to-foam-weight ratio.

Additional tests were completed to:

1. Evaluate on-site generated foam in relatively constant thickness oil slicks.
2. Evaluate on-site foam when an excess of oil was present.
3. Evaluate the effect of surface collecting agents.

The data in Table 9 show that the on-site generated foam sorbed about the same quantities of low viscosity oils as did polyurethane foams tested by others (see Reference 2). The sorption of Bunker C was lower than values previously reported for similar oils because of the short exposure time and lack of agitation while obtaining values reported in Table 9. The primary difference between the data reported here and those reported by others was that the exposure period allowed in the present series of tests is only one minute with no agitation, whereas an exposure

TABLE 9

SORPTION EVALUATION OF ON SITE GENERATED FOAM UTILIZING SURFACE-COLLECTING AGENTS

Foam Description:

Density, lb/ft^3	2.1
Pores/Inch	51
Tensile Strength, lb/in^2	3.1
Compressibility, lb/50 in^2	
25% Compressed	15
50% Compressed	27
65% Compressed	44

Oil Description:

1. No. 2 Diesel Fuel
2. Blend of No. 2 Diesel and Bunker C Fuels
3. Carnea 21 Oil
4. Bunker C Fuel

Properties:

	Test Oil No.			
	1	2	3	4
Gravity, °API at 60°F	42.3	24.5	25.1	10.8
Viscosity at °F, cs				
60	2.6	27	75	2700
77	2.2	13	40	1000
80	2.1	12	36	890

Test Conditions:

Water (75°F) contained in a 3-ft diameter reservoir was treated with four drops of Oil Herder® placed 90° apart and at the reservoir wall. A measured 250 milliliters of oil were poured into the water at the center of the reservoir. The diameter of the lens was measured after the oil had collected into a near perfect circle (about 15 minutes). An accurately weighed quantity of foam (about 10 grams for large pieces) was applied to the oil lens near the center. A stop watch was started when the foam was applied. The foam was removed 1.0 ± 0.01 minute after being applied, and placed in a tared container. The total weight of liquids sorbed was determined immediately. The foam was squeezed vigorously by hand. The recovered water and oil were separated and measured. The oil remaining on the water was recovered and measured.

TABLE 9 (Continued)

Test No.	Oil				Foam Cube Dimension, In.	Sorption Values			
	No.	Specific Gravity	Viscosity, cs	Thickness, mm		Oil/Foam Gal./Lb	Water/Foam Gal./Lb	Oil to Water Ratio	Oil to Foam Ratio (Weight)
1	1	0.808	2.3	0.055	2	2.34	1.52	1.6	16
2	1	0.808	2.3	0.082	2	2.22	1.05	2.1	15
3	1	0.808	2.3	0.090	2	2.34	1.87	1.2	16
4	1	0.808	2.3	0.055	1	2.34	1.52	1.6	16
5	1	0.808	2.3	0.082	1/2	2.46	0.82	2.4	17
6	2	0.901	13	0.21	2	3.04	0.18	17	25
7	2	0.901	13	0.18	1	4.45	Nil	--	34
8	2	0.901	13	0.20	1/2	3.74	Nil	--	28
9	2	0.901	13	0.16	2	3.28	Trace	--	26
10	2	0.901	13	0.35	2	3.04	Trace	--	23
11[1]	2	0.901	13	0.35	2	3.04	0.70	4	23
12	2	0.901	13	0.15	1	4.10	Trace	--	31
13	3	0.899	43	0.25	2	1.76	0.12	14	13
14	3	0.899	43	0.25	1	3.74	0.09	38	28
15	3	0.899	43	0.25	1/2	3.74	Nil	--	28
16[2]	4	0.989	1000	0.20	2	0.35	Nil	--	3
17[2]	4	0.989	1000	0.20	1	0.58	Nil	--	5
18[2]	4	0.989	1000	0.20	1/2	1.05	Nil	--	9

---

1) 2" cube completely soaked in 90 seconds. Left in 0.12-inch (thick) slick on water with about 1.8-inch extending into water for 18 hours.

2) Not Collected because oil would be in excess of 1 inch thick. Foam only partially sank; thus, oil-to-foam ratio is a function of surface area of foam only, because essentially no oil was imbibed into the center of the cube.

period of fifteen minutes with agitation was used in the tests of Reference 2. When the foam was applied to the central portion of an oil lens which was maintained at an equilibrium thickness by a surface-collecting agent, the surface tension gradient established by the agent continuously drew the oil into the area occupied by the foam so that the oil thickness adjacent to the foam remained nearly constant, resulting in increased oil sorption by the foam. Thus, a dynamic system, utilizing either diversionary booms or surface collecting agents to continuously concentrate the oil, will result in more efficient performance of a foam spill recovery system than data obtained under static conditions.

Data in Figure 12 and Table 10 show compressive values for two samples of foam at different dates. Though the crosslinking reactions are near completion in one or two minutes after the foam components are well mixed, further reactions continue for a long period of time and increase slightly the rigidity of the foam.

TABLE 10

COMPRESSIBILITY OF ON-SITE GENERATED POLYURETHANE FOAM

Test Date	Compressibility, lb/50 in²					
	July 22 Foam			November 29 Foam		
	25%	50%	65%	25%	50%	65%
July 27	10	13	22	--	--	--
December 1	13	19	29	7	10	14
February 9	--	--	--	12	17	25

Foam Production Equipment

The two-component polyurethane foam recipe described in Table 2 has been produced both by hand mixing and commercial foaming equipment.

Commercial equipment used was a Graco Hydracat Variable Pumping Unit equipped with a Binks 18 FM gun (Figure 13). This unit consists of a President Model 205-038 Series D Air Motor driving two Graco Size 2 displacement pumps (one variable) mounted on a portable frame, with associated filters and hoses. A necessary part of the equipment is the gun flush equipment consisting of a 5-gallon Monark Hydra Spray unit Model 226-153 Series "A" and hose (Figure 13 extreme left).

The displacement pumps are attached to 55-gallon drums of components mounted on portable barrel racks (Figure 13 rear). The equipment is driven by compressed air (40 to 140 psi) at a rate of about 15 CFM. With a Binks 18 FM gun (Figure 14, left) this equipment pours 300 to 360 pounds of foam per hour (5 to 6 pounds per minute). Use of a mixing device (Figure 14) might increase the pouring rate. Untrained personnel have operated the equipment and have made good quality foam with only 30 minutes of instruction.

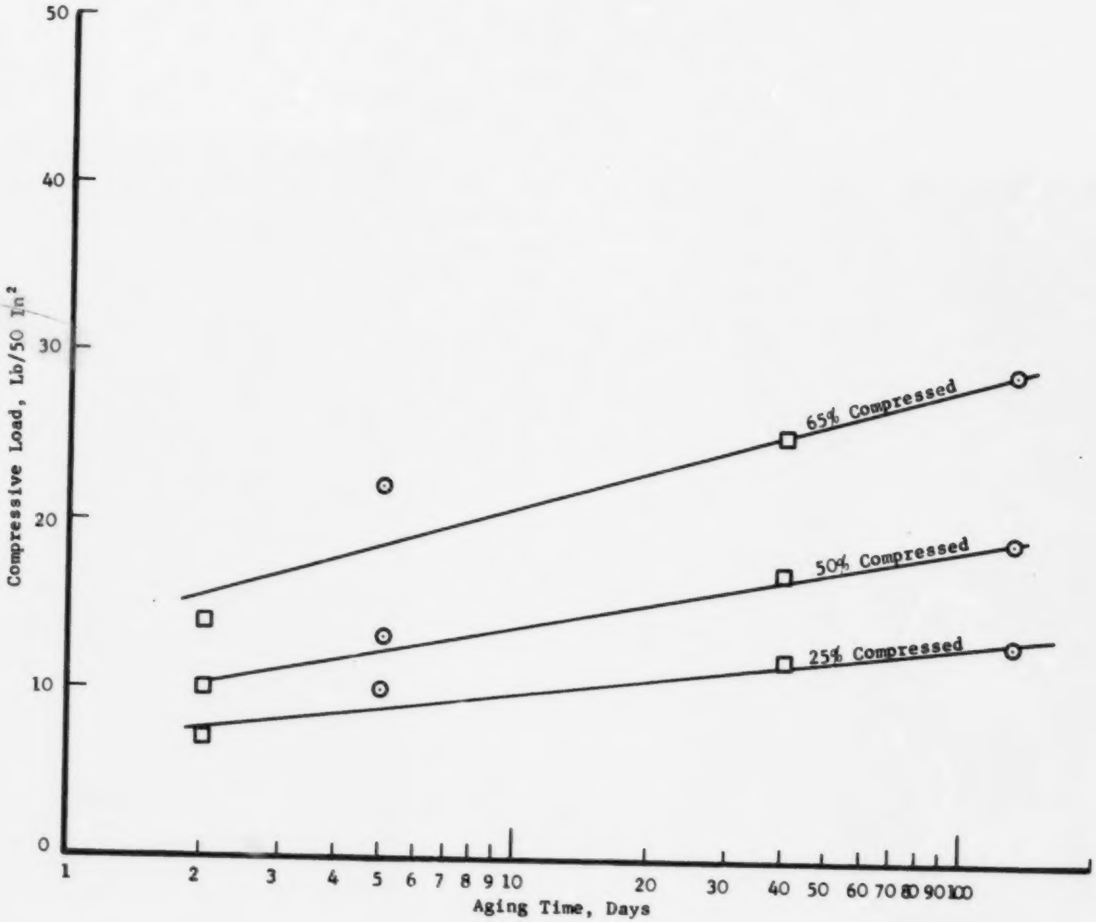


FIGURE 12 - AGING TIME VERSUS COMPRESSIVE LOAD TO OBTAIN 25%, 50%, AND 65% COMPRESSION OF ON-SITE GENERATED POLYURETHANE FOAM

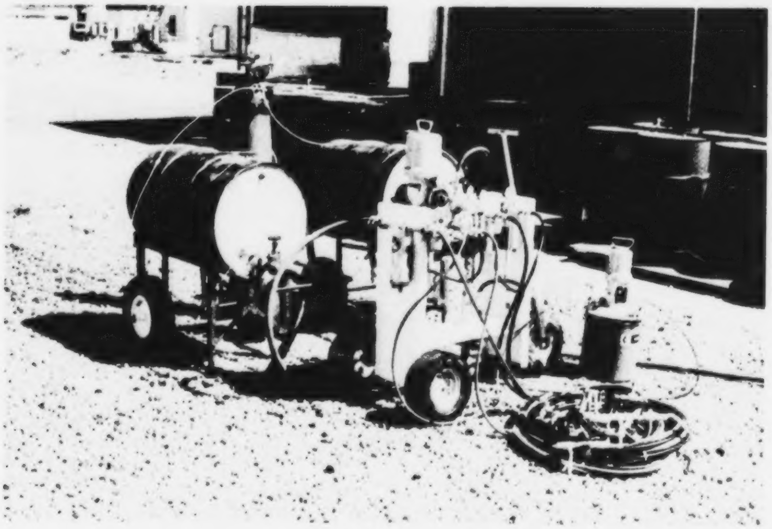


Figure 13 - PORTABLE FOAMING EQUIPMENT

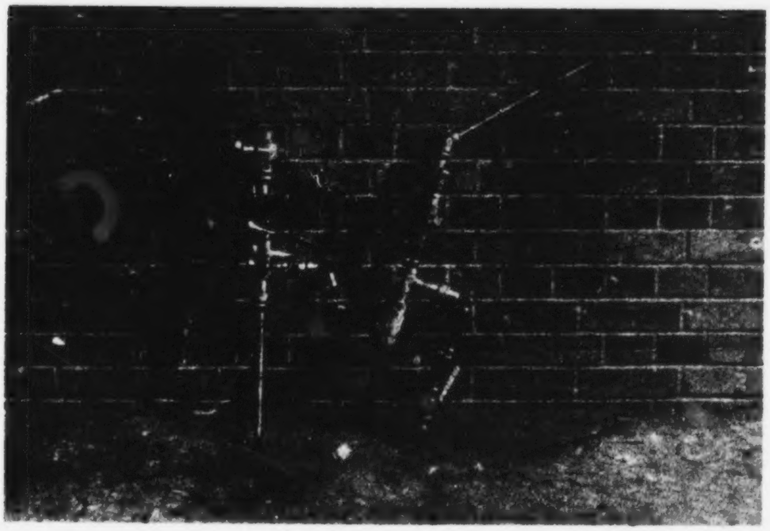


Figure 14 - MIXING HEADS USED WITH PORTABLE FOAMING EQUIPMENT

Larger scale equipment capable of producing 40 to 50 pounds of foam per minute was also used. Any of the currently-available foam equipment which can pump 500 to 1000 cp materials and blend through a mixing head at a ratio of two parts Component "B" (polyol) to one part Component "A" (isocyanate) may be used.

Foam Production

A typical foam production operation is shown in Figure 15. On this day the ambient temperature was 60°F. Foam was being poured at a rate of 360 pounds per hour. The rise time was about 45 seconds and the foam was tack free in four minutes. The resulting 2.2 lb/ft^3 foam is shown in Figure 16. When large batches (over one ton) are required the foam might be poured on a moving belt as described in Figure 17.

Foam was made utilizing a Polymer Services Corporation foam unit (Figure 18). The mixed components were applied at a rate of about 40 lb/min to plastic sheets and paper spread on the ground. The ambient temperature was 55°F and a light mist was falling. A 2.5 lb/ft^3 foam suitable for sorbing oil was produced.

Once produced, foam can be stored in rolls as shown in Figure 19, until needed for mulching and distribution as shown in Figure 20.

Natural Degradation

We have noted that polyurethane foams, exposed to sunlight, degrade with time. Qualitatively, the on-site generated foam appears to degrade more rapidly than the commercially-available foams, becoming friable and easily crumbled. Thus, it appears that on-site foam should be more easily attacked by bacteria and converted to CO_2, water, etc. We believe this an advantage, because any foam which is lost from the system will be decomposed by natural processes in a shorter time than commercially-available polyurethane foam.

The prepared components for on-site foaming have an observed shelf life of six months before becoming insufficiently reactive for satisfactory foaming. This life might be extended by the use of catalysts during the foaming operation; however, we have not studied possible catalysts.

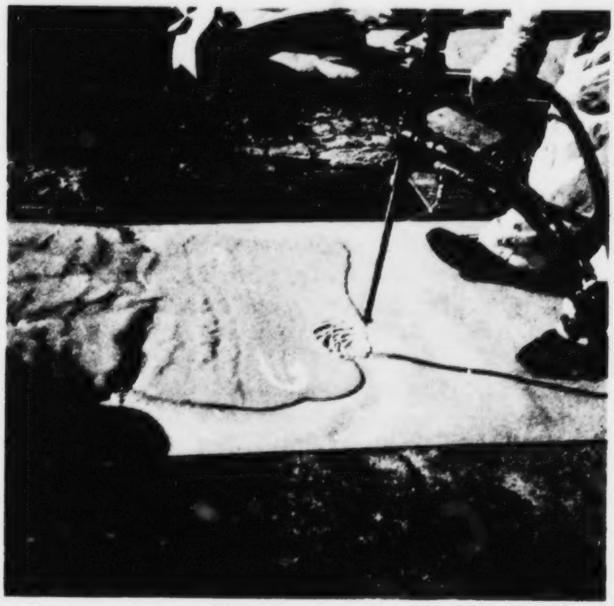


Figure 15 - POLYURETHANE FOAM PRODUCTION UTILIZING A PORTABLE GRACO HYDROCAT UNIT

Figure 16 - POLYURETHANE FOAM PRODUCED UTILIZING PORTABLE GRACO HYDROCAT UNIT

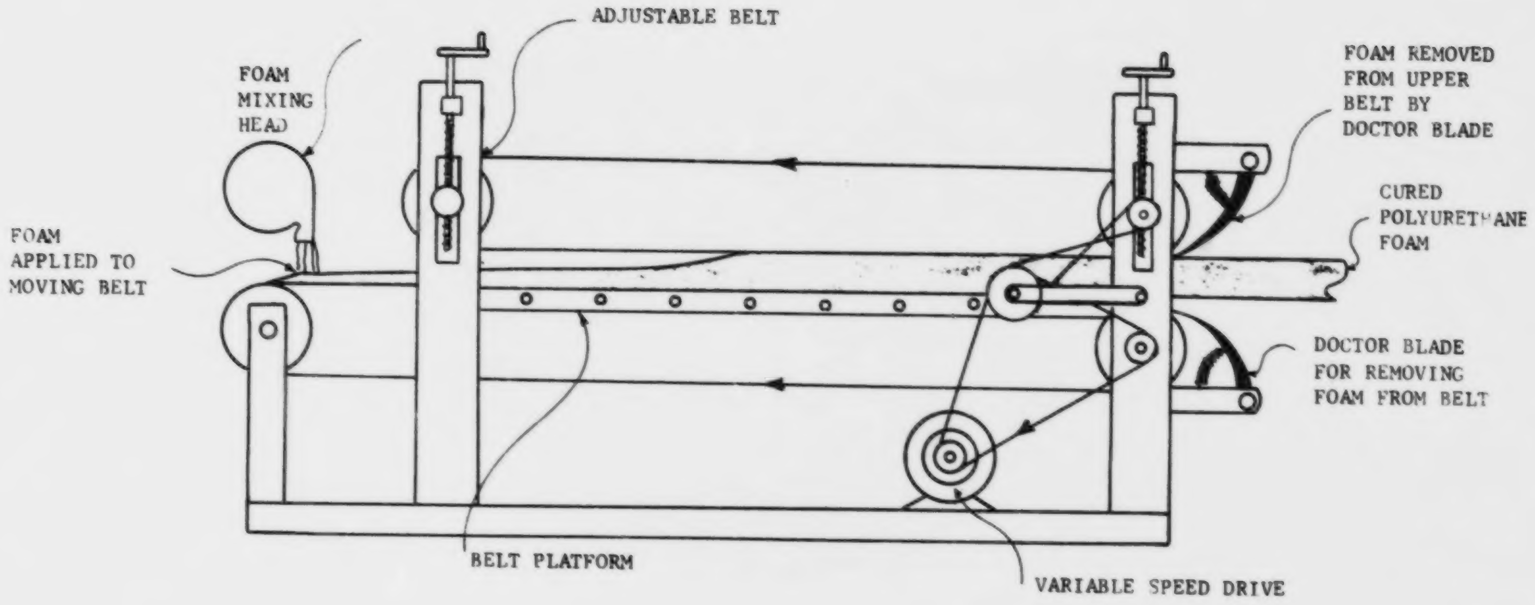

ADJUSTABLE BELT
FOAM MIXING HEAD
FOAM APPLIED TO MOVING BELT
FOAM REMOVED FROM UPPER BELT BY DOCTOR BLADE
CURED POLYURETHANE FOAM
DOCTOR BLADE FOR REMOVING FOAM FROM BELT
BELT PLATFORM
VARIABLE SPEED DRIVE

FIGURE 17 - SCHEMATIC OF CONTINUOUS BELT FOR MAKING POLYURETHANE AT SITE OF OIL SPILL

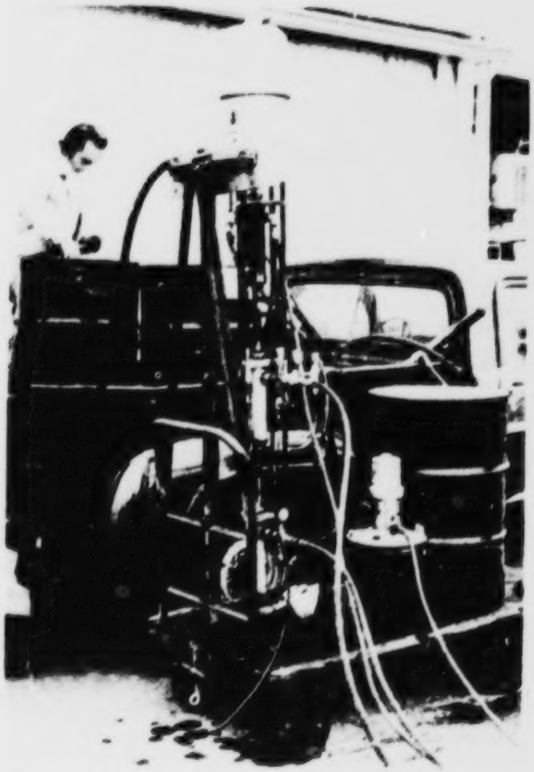


Figure 18 - CONTRACT FOAM EQUIPMENT

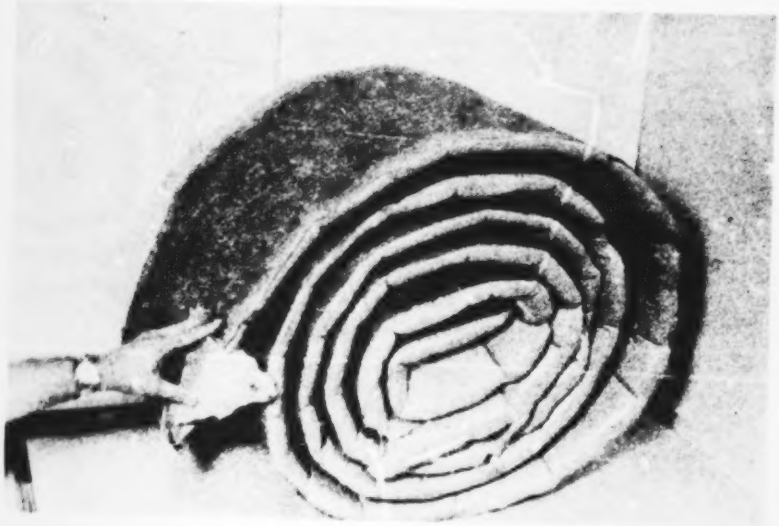


Figure 19 - POLYURETHANE FOAM BUN FORMED INTO ROLL

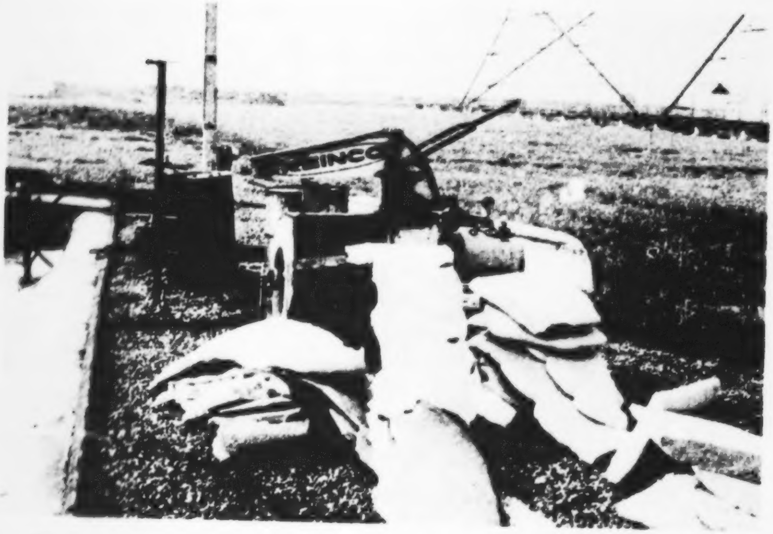


Figure 20 - FOAM BUNS READY FOR MULCHING UTILIZING A REINCO HAY SPREADER

SECTION VII

SORPTION

Fundamental to the operation of a marine oil recovery system utilizing a sorbent material is the sorption of oil from a slick by a sorbent floating on or near the water surface. The nature of the process of absorption of oil from a slick by a water-saturated oleophilic block may be understood by considering an elementary, two-dimensional analysis based on the simplified illustration of Figure 21. The foam particle may be assumed to have a circular equivalent of radius, r_e, into which oil is absorbed uniformly about the circumference at a total rate $\dot{Q}$. Ignoring the vertical diffusion of oil through the matrix, the oil flux with the material is

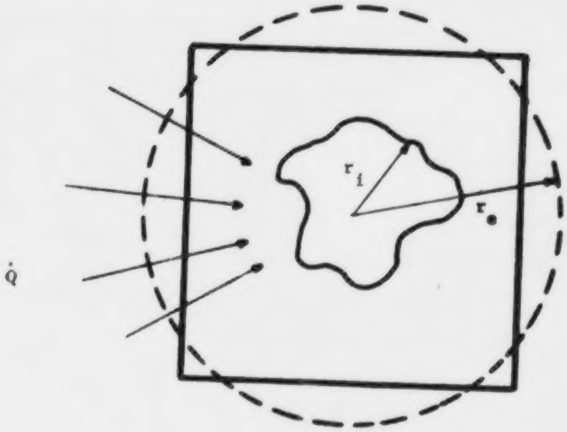


FIGURE 21 - ABSORPTION OF OIL FROM A SLICK BY A POROUS OLEOPHILIC BLOCK

$$q = \frac{\dot{Q}}{2\pi r d_s} \qquad (1)$$

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where r is the local radius, and d_s is the depth of the slick, assumed to be the depth of the oil layer within the block. The pressure gradient within the block then becomes

$$\frac{dP}{dr} = \frac{\mu \dot{Q}}{2\pi r d_s K} \tag{2}$$

where μ is the oil viscosity and K is the permeability of the sorbent material. This equation may be integrated, subject to the boundary conditions

$$P\Big|_{r = r_e} = 0; \quad P\Big|_{r = r_i} = \frac{-\Delta\sigma\Sigma_e}{\phi} \tag{3}$$

where $\Delta\sigma$ is the interfacial driving force, Σ_e is the effective specific surface, and ϕ is the porosity of the sorbent material (see Reference 3). When this is done the result may be solved for $\dot{Q}$.

$$\dot{Q} = \frac{2\pi d_s \Delta\sigma K \Sigma_e}{\mu \phi} \left[\ln\left(\frac{r_e}{r_i}\right)\right]^{-1} \tag{4}$$

Noting that the volume of oil may be found from the relation

$$Q = \pi(r_e^2 - r_i^2) \tag{5}$$

The rate of absorption may be found as

$$\frac{dQ}{dt} = \frac{2\pi d_s \Delta\sigma K \Sigma_e}{\mu \phi} \left\{\ln\left[\frac{1}{\left(1 - \frac{Q}{\pi r_e^2}\right)^{1/2}}\right]\right\}^{-1} \tag{6}$$

This equation may be integrated to obtain

$$\frac{1}{4}\ (1 - \hat{Q})\ \ln(1 - \hat{Q}) + \hat{Q} = \hat{t} \tag{7}$$

where

$$\hat{Q} = \frac{Q}{\pi r_e^2} \tag{8}$$

and

$$\hat{t} = \left(\frac{\Delta \sigma \, d_s \, K \Sigma_e}{\phi \, r_e^2} \right) t \tag{9}$$

This relation is plotted in Figure 22.

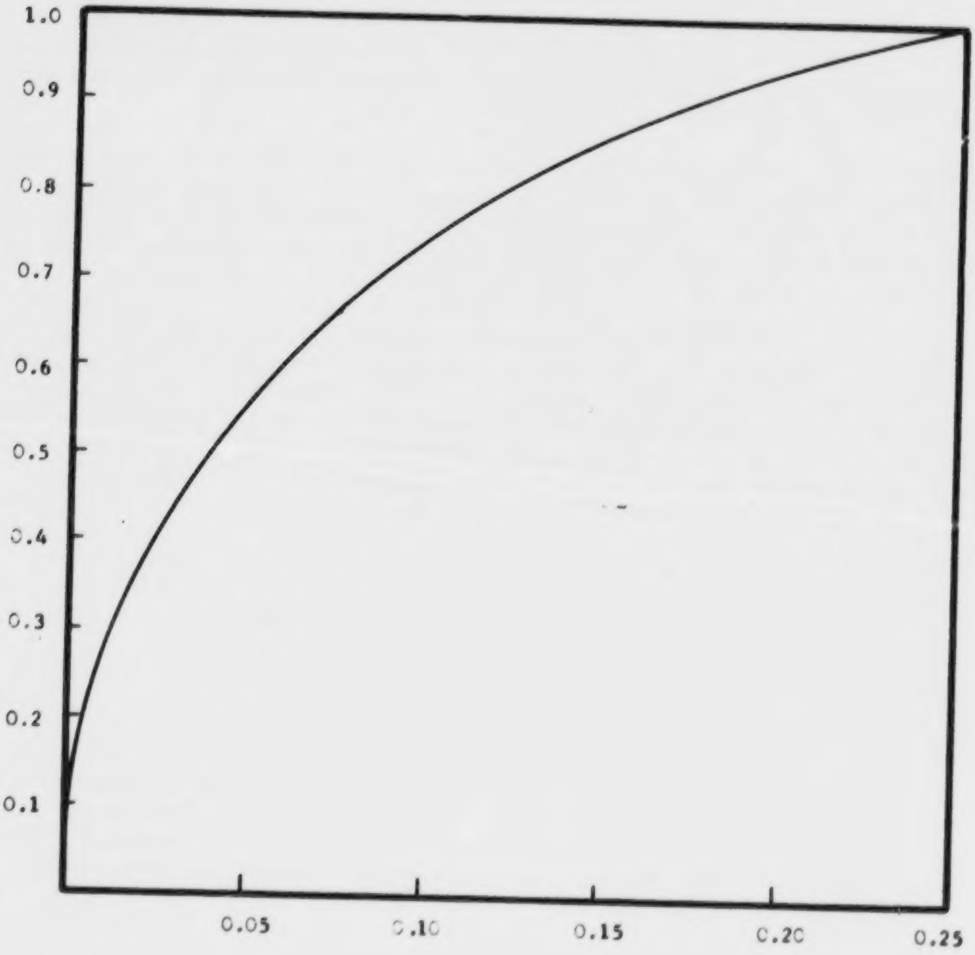


FIGURE 22 - DIMENSIONLESS VOLUME ABSORBED FROM A SLICK BY A WATER SATURATED OLEOPHILIC BLOCK AS FUNCTION OF DIMENSIONLESS TIME

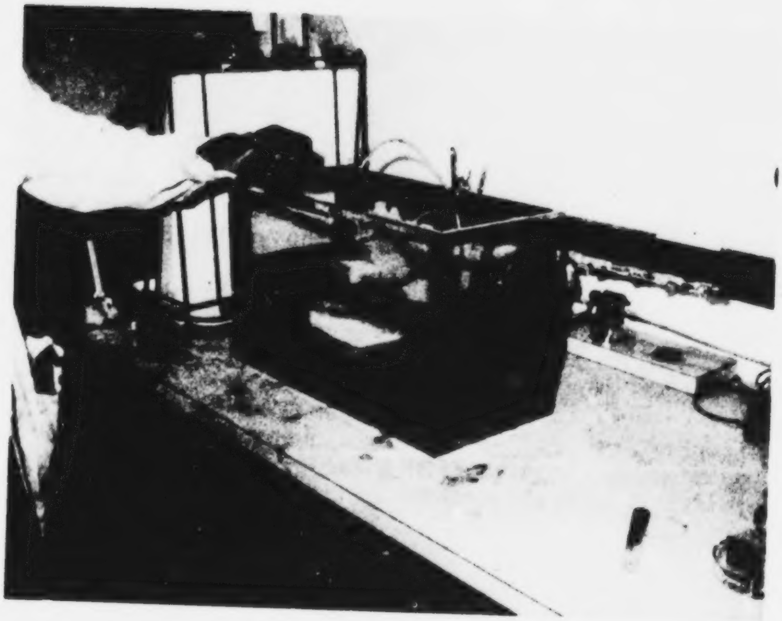
A series of experiments was undertaken to characterize the performance of polyurethane foam as an oil sorbent. During the initial experiments, material samples consisting of cubes of uniform dimension were soaked in slicks of No. 2 diesel oil in the glass-walled tank shown in Figure 23. The experimental procedure used is described in Table 11, Procedure A.

Variations in sorption characteristics of the order of 10% were observed between the on-site generated foam materials produced at different times.

During these early experiments with previously unused foam, it was found that a large fraction of the fluids absorbed (of the order of 20%) is retained within the blocks of foam even after extensive hand and mechanical squeezing. This material consists primarily of oil. Some fractionation of the oil may also occur within the foam, particularly in the case of crude oils, as in some cases it was found that the residual material remaining within the foam after normal squeezing had a specific gravity about 5% less than the original oil.

In experiments with heavier oils, whose properties are shown in Figures 24 and 25, the soaked foam was squeezed mechanically with a pressure of 170 lb/ft^2 in the "mule's foot" squeezer of Figure 26 and the volume of effluent recovered together with its oil content were measured directly as outlined in Table 11, Procedure B. No correction was made for the residual material remaining within the foam matrix after squeezing, as it was assumed that commercial squeezing operations would be similarly inefficient. Results of experiments conducted with Carnea 15 (a refined oil) are shown in Figures 27 through 30. From Figures 27 and 28 it can be seen that total volumes and oil volumes recovered increased with slick depth for any soaking time up to the maximum of 20 minutes tested. Oil-water ratios of the recovered effluent also improved with increasing slick depth. Improved performance might be expected for thin slicks in the presence of waves or currents, because it was observed that oil-free areas may appear about foam particles within thin slicks in the tank. To determine the effects of recycling on foam performance, foam samples were presoaked in oil or water and then squeezed near-dry for use in the sorbent tests. Results from these experiments are shown in Figures 29 and 30. It may be seen that prior exposure to either oil or water generally results in relatively poor performance for soaking times of less than about 15 minutes (900 seconds).

The results of the soaking experiments conducted with the other oils whose properties are included in Figures 24 and 25 in a slick which was initially 0.05 in. (1.3 mm) deep are shown in Figure 31. These figures indicate that recovered volumes of both total effluent and oil may be generally high for the light oils but may reach a minimum at an oil viscosity of about 30 to 40 cs. In Figure 32 the volume fraction of oil varies from approximately 20 to 30 percent. Again, though results are mixed, performance is generally better in the cases of the lighter oils tested in this series; however, performance appears to reach a minimum at an oil viscosity of about 30 - 40 cs and would improve for higher viscosities.



a) Soaking foam

b) Removing and draining foam

FIGURE 23 - BENCH-SCALE SORPTION TEST APPARATUS

TABLE 11

PROCEDURES USED TO STUDY OIL SORPTION BY FOAM BLOCKS

Equipment

1. Cubes cut from on-site generated foam on band saw to desired size
2. 10-gallon, 10-1/2-inch x 9-1/2-inches x 12-inches aquarium
3. 1/4-inch mesh stainless screen
4. Depth indicator micrometer mounted on a bracket
5. Mettler balance
6. 100-ml and 500-ml graduated cylinders
7. Mule's-foot squeezer - 4-1/2-inch I.D. x 10-inch long thin wall tubing. Steel stock 4-inch diameter x 4-inches long cut at 20° angle used as plunger. Plunger weight = 14 lb (170 lb/ft^2 pressure applied.)
8. Tretolite C-10 demulsifier.

Procedure A

1. Fill tank with water
2. Put drain screen in tank
3. Measure level with micrometer
4. Using graduated cylinder add measured amount of oil
5. Measure level with micrometer
6. Weigh the foam in a container on Mettler balance
7. Place foam on oil slick and leave for the required amount of time
8. Pull foam cubes with screen and let drain for 30 seconds
9. Place cubes in weighing container and re-weight
10. With micrometer measure new water-oil level
11. Calculate the amount of oil and water soaked up by the foam from the change in oil thickness

$$V(\%) = \frac{\left(1 - \frac{\Delta M}{\Delta V}\right)}{(1 - SPG)} \times 100$$

Procedure B

Same as above for steps 1 - 9.

10. With mule's foot squeezer, remove oil and water from foam
11. Measure volumes of oil and water directly in graduated cylinders, using demulsifier if necessary to aid oil/water separation

Environmental Conditions

Indoors, 72°F
No agitation

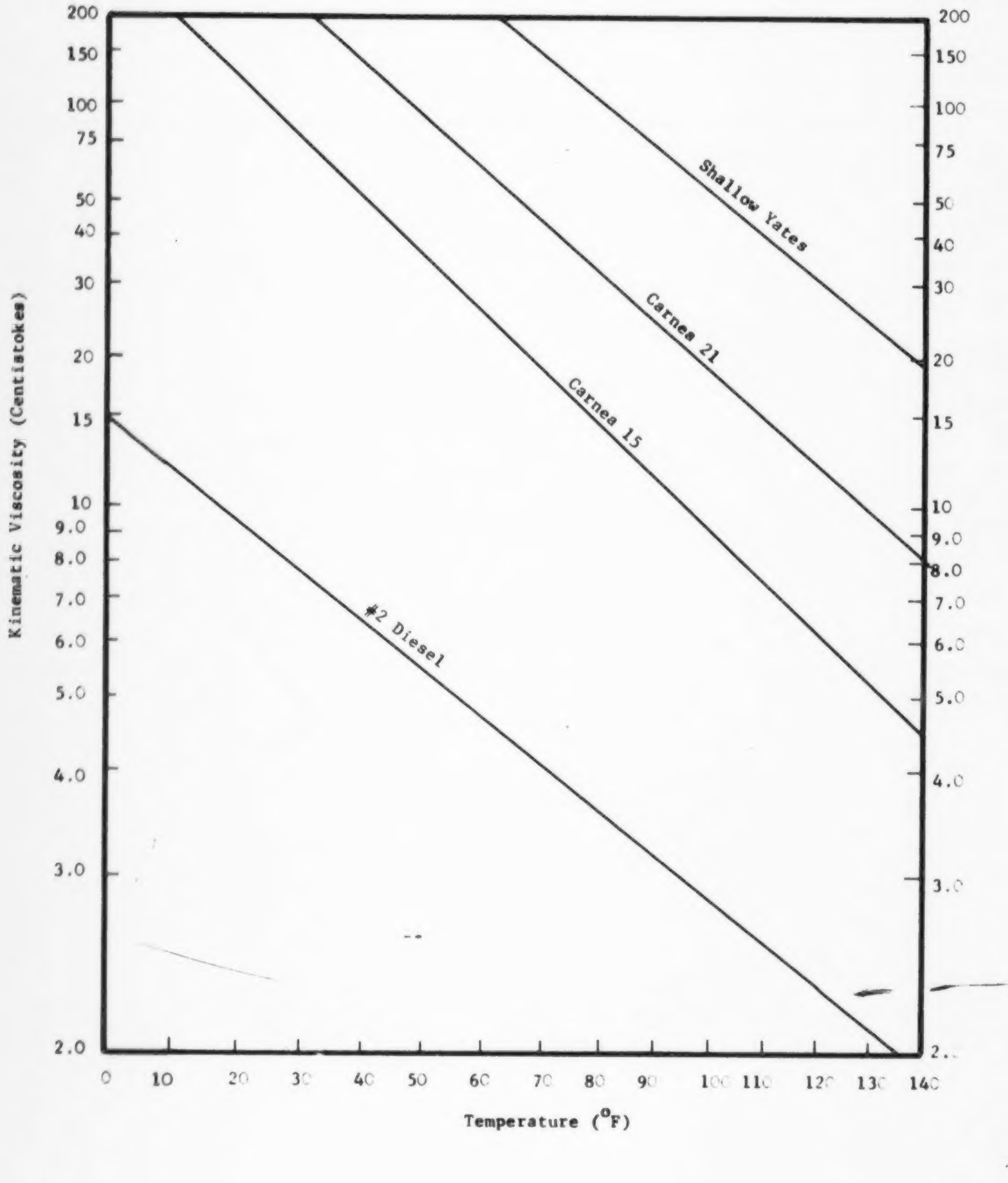


FIGURE 24 - VISCOSITY OF TEST OILS

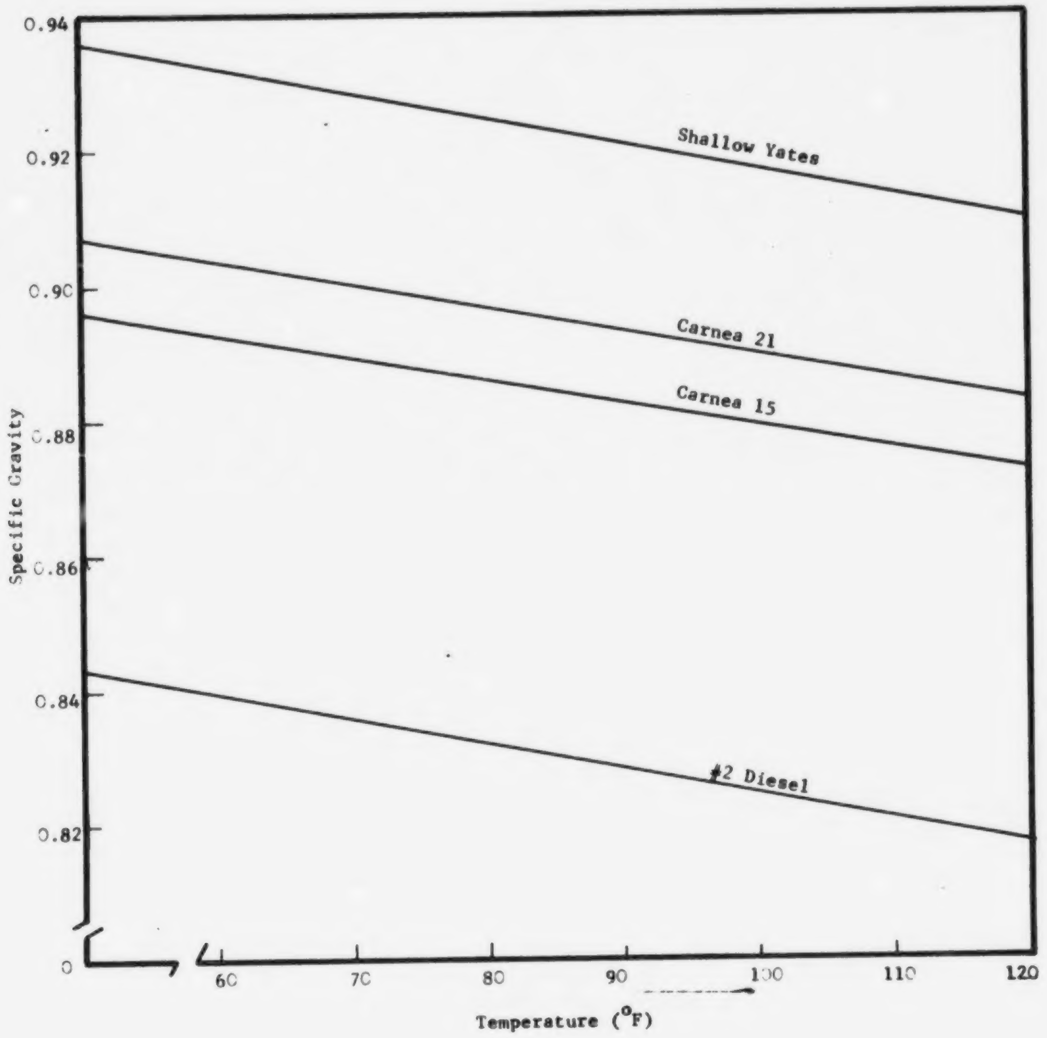
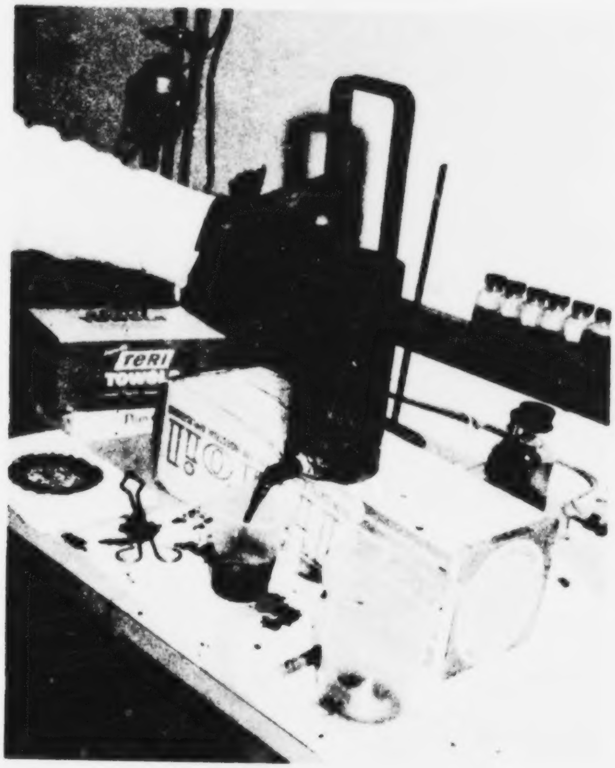


FIGURE 25 - SPECIFIC GRAVITY OF TEST OILS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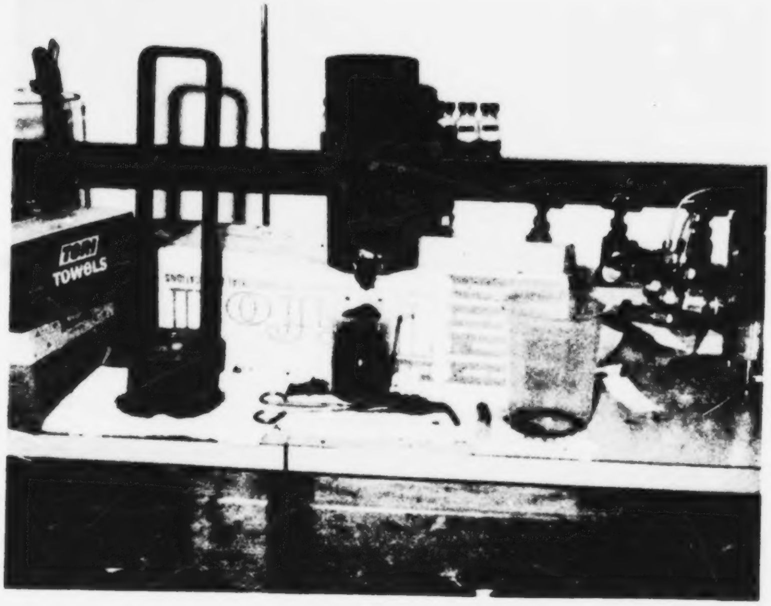
a) Squeezing No. 2 oil from foam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b) After use with No. 6 oil

Figure 26 - "MULE'S FOOT" SQUEEZER

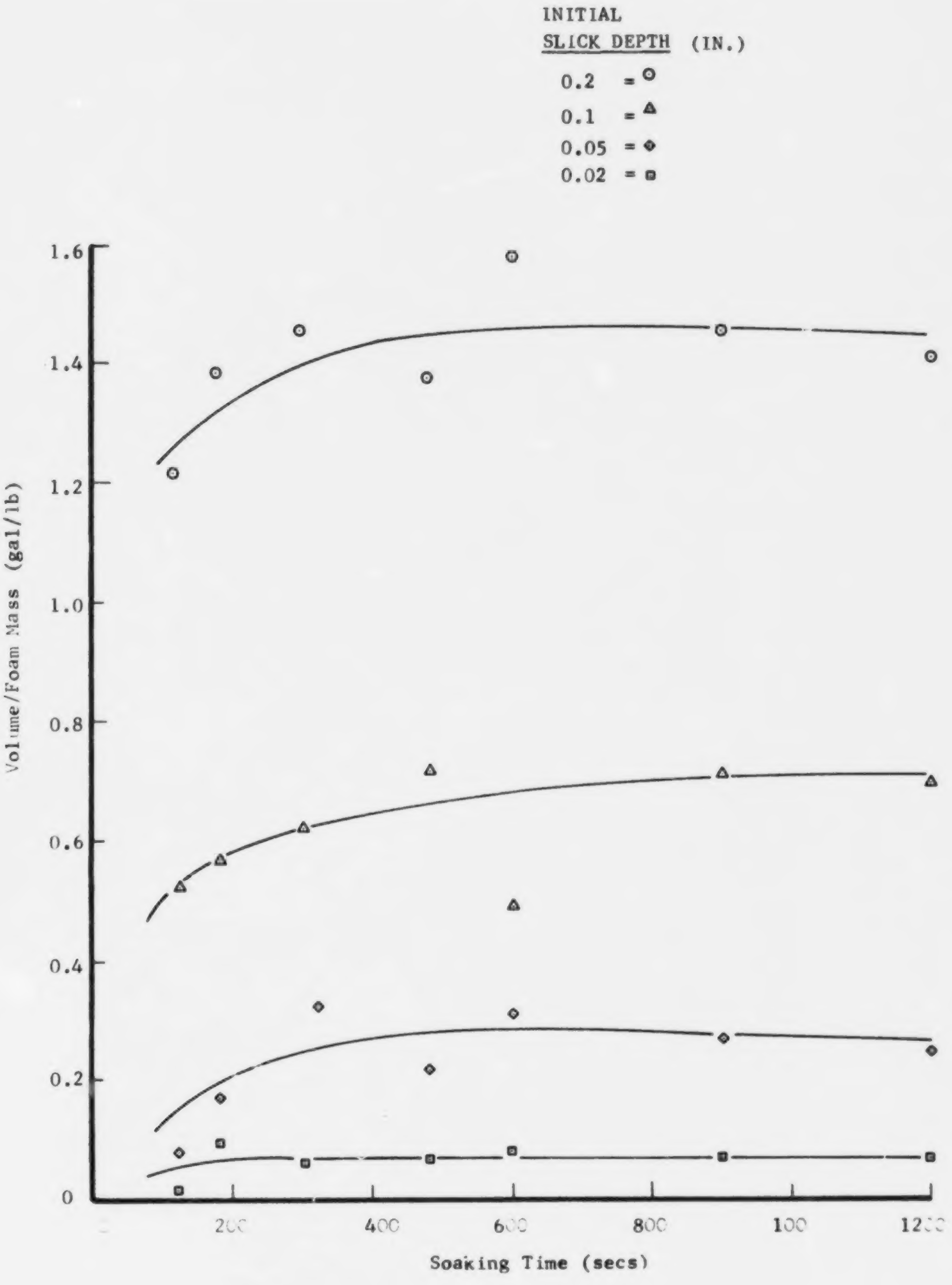


FIGURE 27 - OIL VOLUME RECOVERED, CARNEA 15

Experimental procedure is decribed in
Table 11, Procedure B.

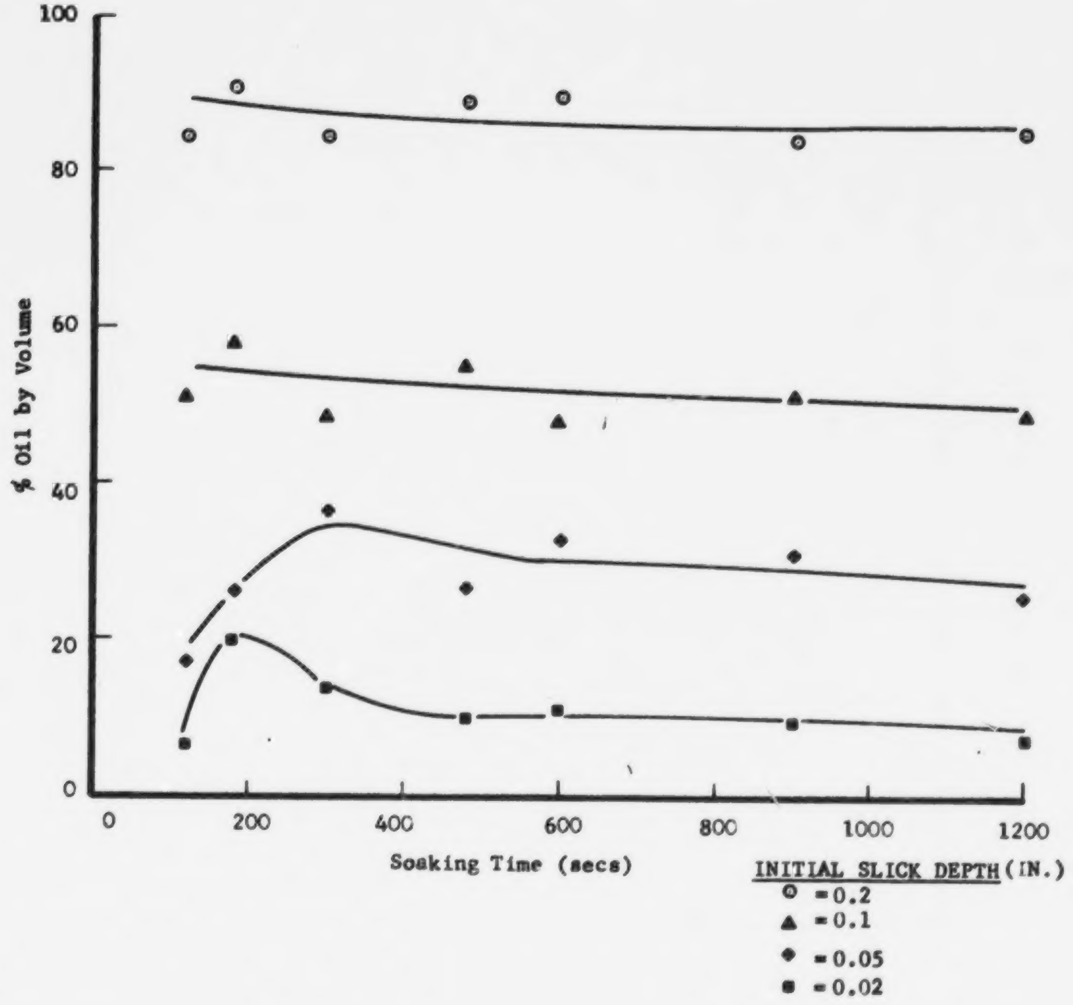


FIGURE 28 - PERCENT OIL IN EFFLUENT RECOVERED, CARNEA 15

Experimental procedure is described in Table 11, Procedure B.

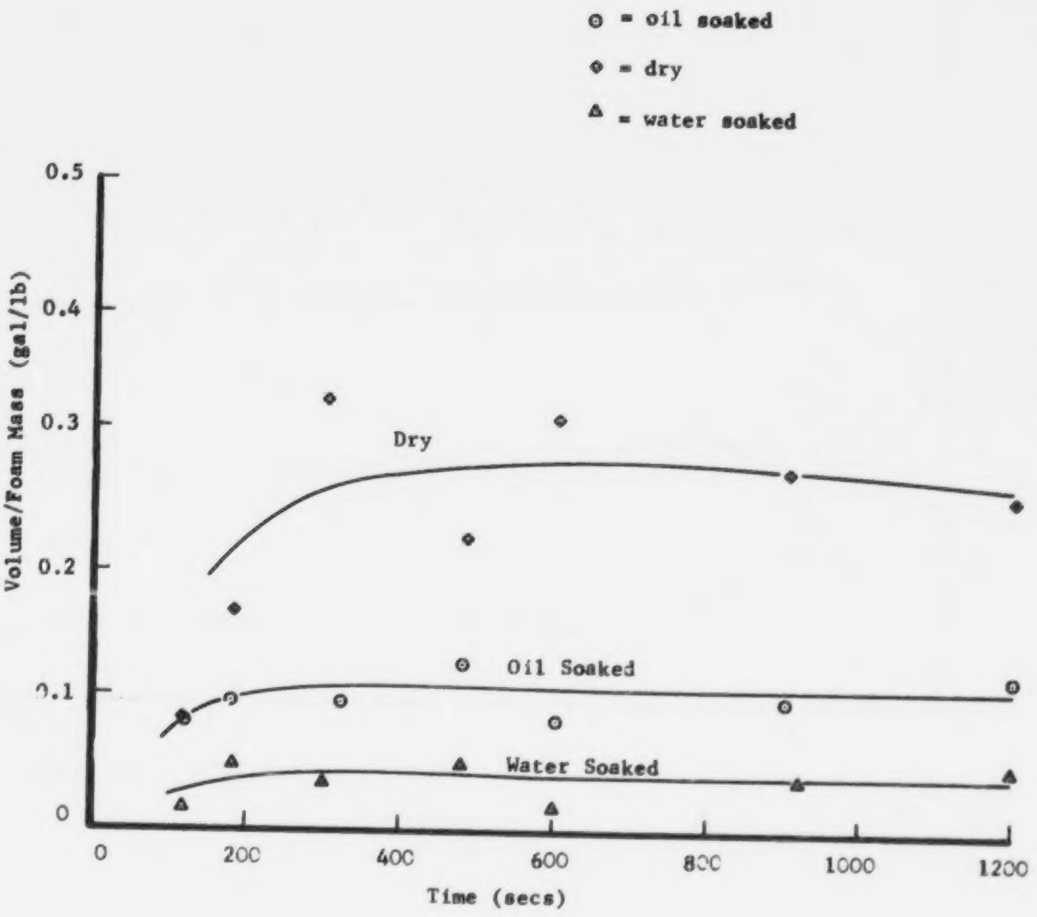


FIGURE 29- OIL VOLUME RECOVERED FROM SORPTION OF CARNEA 15

Experimental procedure as described in Table 11, Procedure B.

Initial slick thickness = 0.05 in.

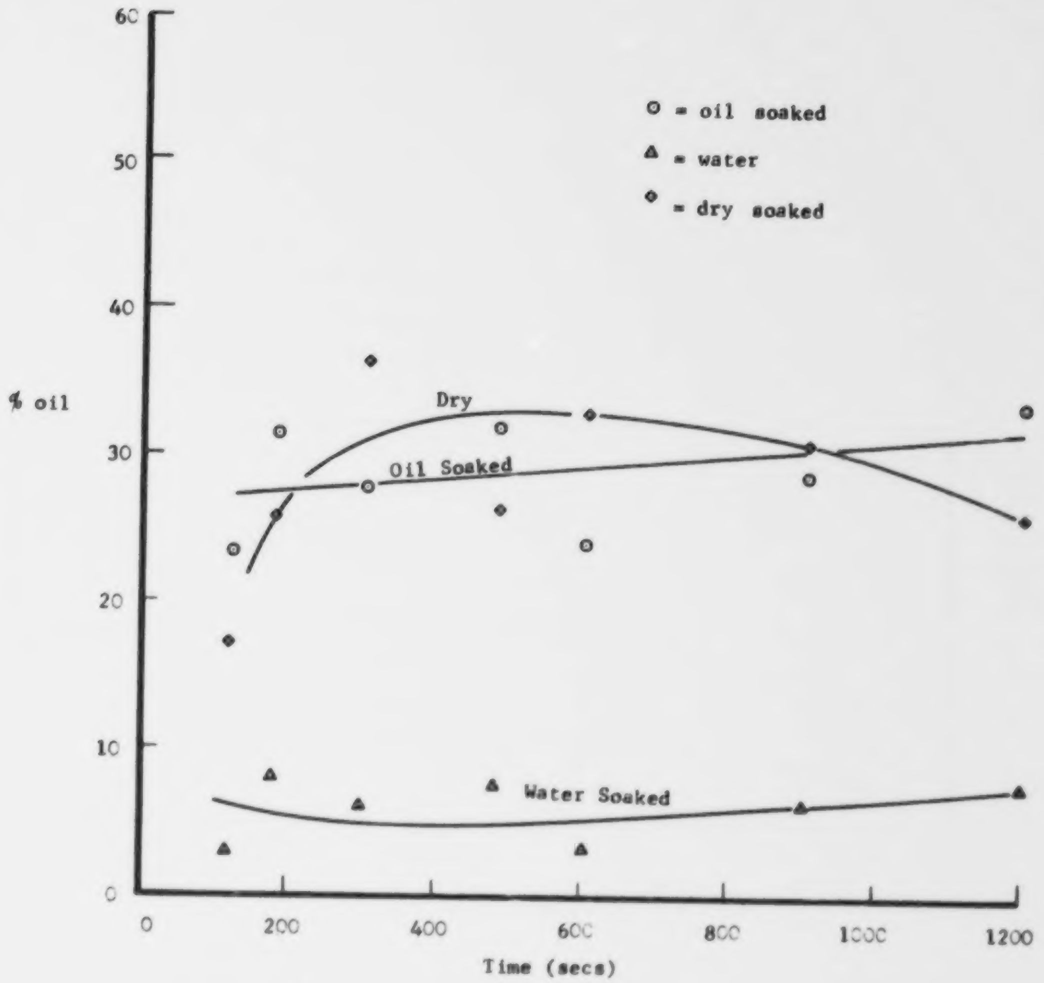


FIGURE 30- PERCENT OIL IN EFFLUENT RECOVERED FROM SORPTION OF CARNEA 15

Experimental procedure is described in Table 11, Procedure B.
Initial slick thickness = 0.05 in.

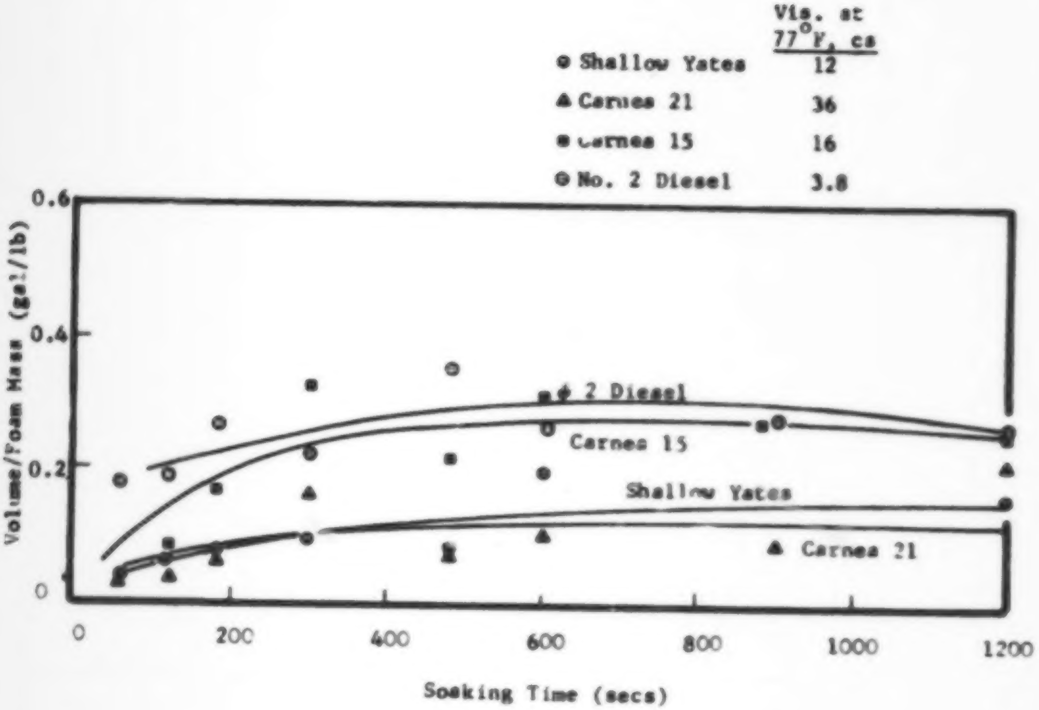


FIGURE 31 - OIL VOLUME RECOVERED FROM 0.057 IN. SLICK BY 2-INCH SORBENT CUBES

Experimental procedure is described in Table 11, Procedure B.
Initial slick thickness = 0.05 in.

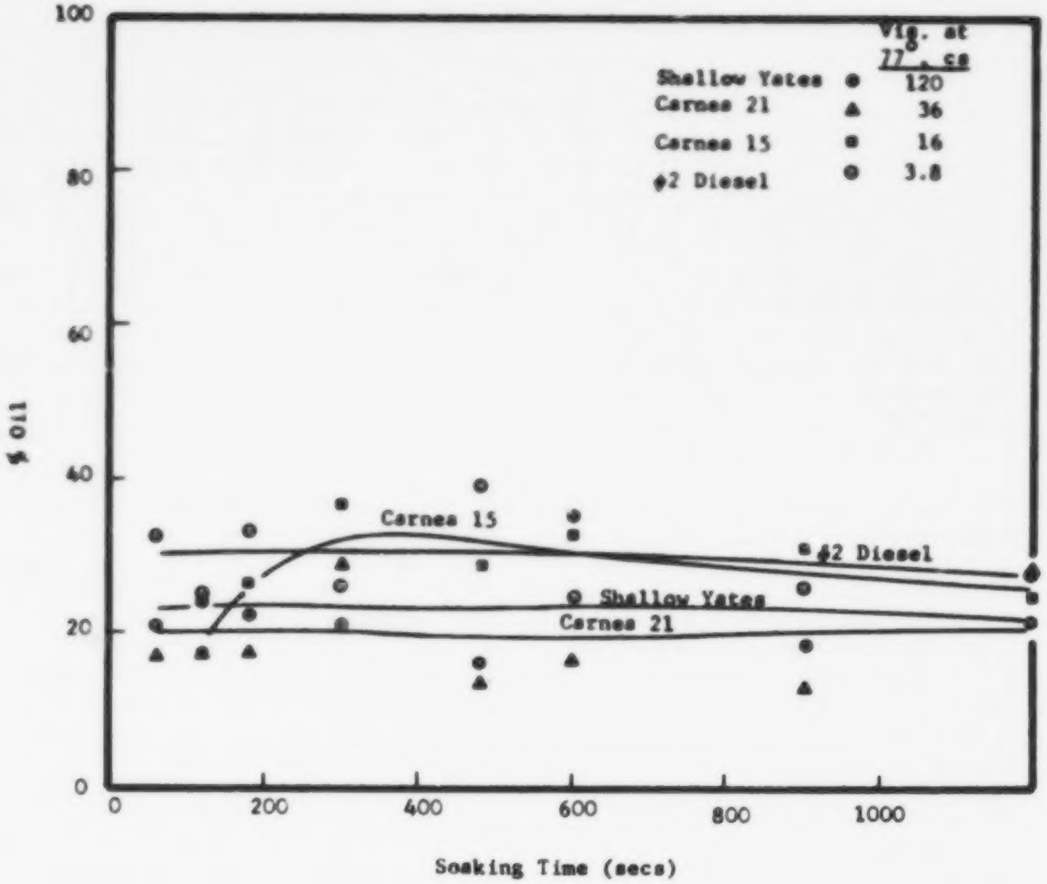


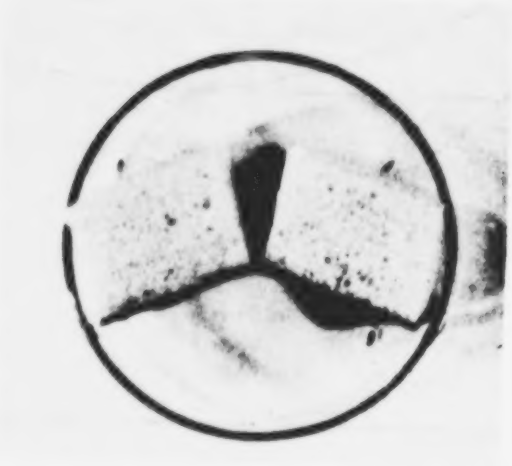
FIGURE 32 - PERCENT OIL IN EFFLUENT RECOVERED FROM 2-INCH SORBENT CUBES

Experimental procedure is described in Table 11, Procedure B.

Initial slick thickness = 0.05 in.

Bench-scale sorption experiments were also performed using No. 6 Fuel Oil of a viscosity of about 5000 cs at 72°F. When 2-inch foam cubes were placed on a slick consisting of 0.02 gal. of No. 6 Fuel Oil for approximately two minutes they did not sink through the oil. No significant quantity of the oil adhered to the surface of the blocks upon their removal from the slick (Figure 33(a)). When strips of sorbed material were forced through the slick, into the water below, and held for two minutes, the oil coated the foam, preventing water from entering its interior. (Figure 33(b)). Small quantities of oil were forced into the sorbent by hydrostatic pressure, but the majority of the interior remained dry. A sample consisting of five 2-inch cubes was placed in the tank and stirred into the slick. Where the sorbent was first exposed to water, the oil did not adhere as readily as to the dry surfaces. Due to the large quantity of oil which adhered to the exterior surfaces of the cubes, large absolute quantities of oil were recovered, and a high percentage oil content of the effluent was observed when the sorbent was squeezed. These results confirm that, although specific oil recovery and effluent purity initially decrease with increasing viscosity, this trend reverses for oils of viscosities above about 200 cs (Shallow Yates) as indicated in Figures 31 and 32. This trend may be explained by considering Figure 34. While the quantity of oil absorbed into the sorbent matrix over short sorption times generally decreased with increasing viscosity due to a decrease in imbibition rates, the quantity of oil which adheres to the exterior of the sorbent particles increases with increasing viscosity. Thus, the total oil recovered, which is the sum of the two, is represented by the bucket shaped curve of the illustration.

The above experiments demonstrated the effects of slick depth, sorption time, and prior foam usage upon the amounts of oil and water sorbed by 2-inch polyurethane foam cubes. The oil content of the recovered fluids, specific oil sorption by the sorbent, and fraction of the oil contained in the slick that is recovered will vary additionally with the areal concentration of the sorbent application. Experiments were undertaken to determine the nature of this dependency using the polyurethane foam mulch proposed for use as the oil sorbent in the full-scale recovery system under investigation, to determine the quantity of sorbent which should be applied to an oil slick to achieve optimum or near optimum performance of the system. The size distribution of the polyurethane foam mulch tested is indicated in Table 12. The apparatus is illustrated in Figure 35 and procedures are described in Table 13. A 0.06 in. slick of No. 2 diesel fuel was floated on a 5-foot diameter tank of water. A measured quantity of foam mulch was dumped on the water and spread evenly over the tank. After a soaking period of two minutes, the sorbent was lifted from the tank in a net, allowed to drain for 30 seconds, and placed in the mechanical wringing device, described in Section XI, page 119ff. The sorbed fluids were wrung from the foam by passing three times between six-inch diameter steel rollers under a linear wringing pressure of 7.5 lb/in. The total effluent volume and oil volume recovered in the wringing process were then measured directly. The entire procedure was repeated for a second cycle using the same sorbent material.



a) Floated on slick

b) Thrust through slick

Figure 33 - RESULTS OF QUALITATIVE EXPERIMENT WITH NO. 6 FUEL OIL

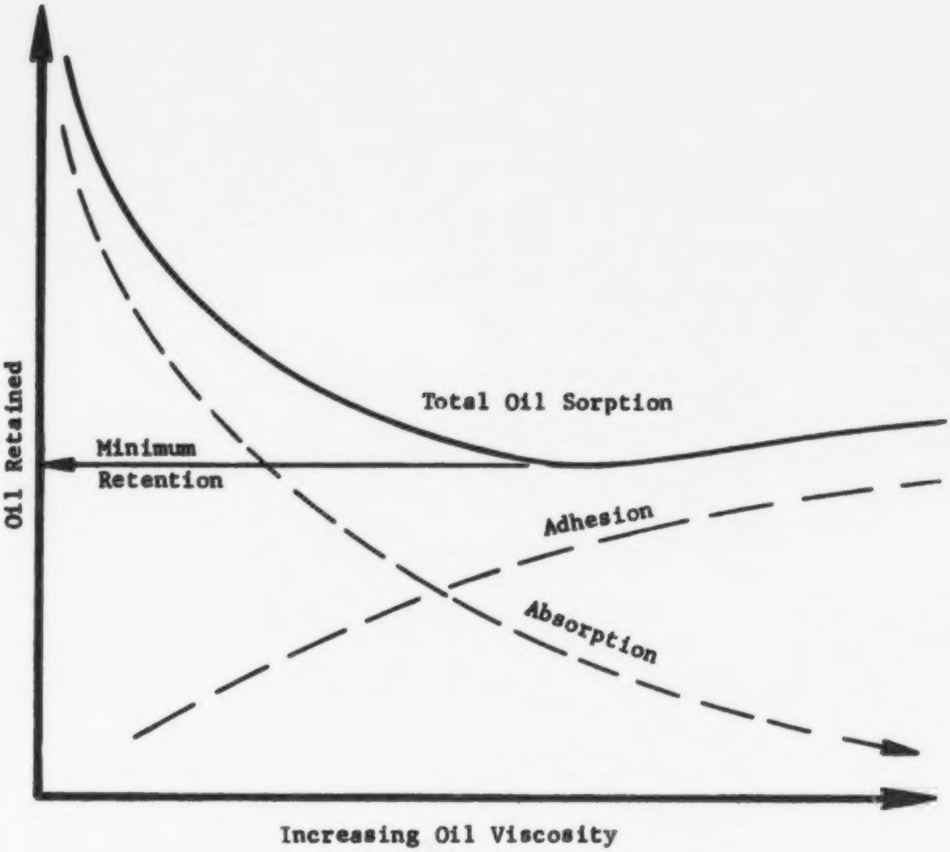


FIGURE 34 - NATURE OF RECOVERY DEPENDENCE UPON VISCOSITY FOR POROUS OIL SORBENT FOR EXPOSURE PERIODS INSUFFICIENTLY LONG TO PERMIT COMPLETE SATURACTION OF THE FOAM BY MORE VISCOUS OILS

TABLE 12

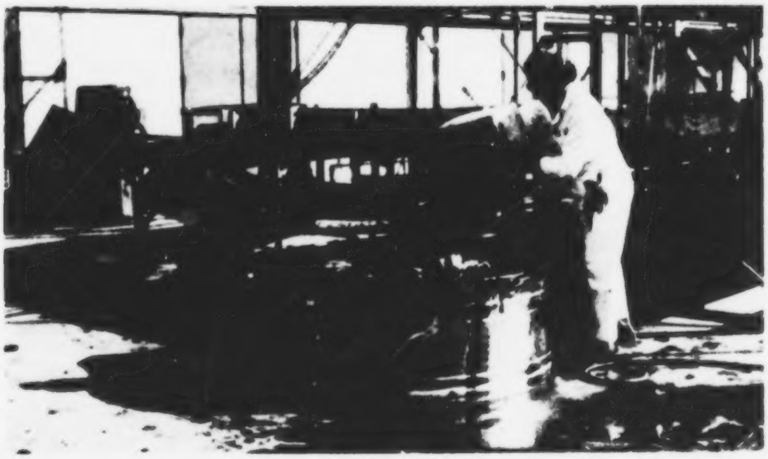
PARTICLE SIZE DISTRIBUTION OF MULCHED FOAM

Conditions:

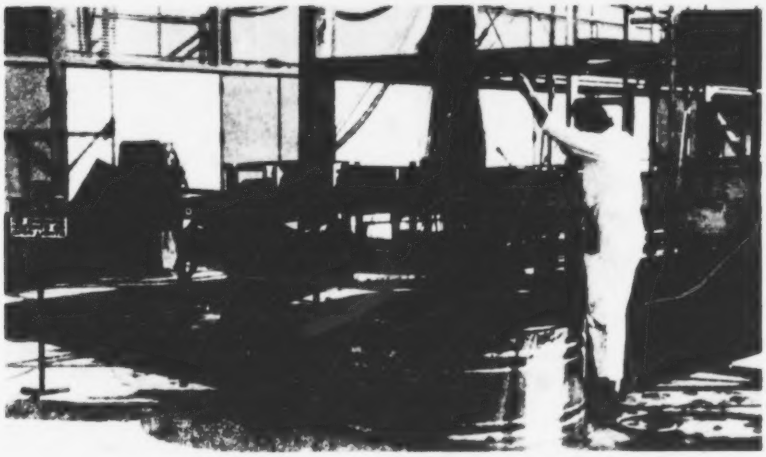
Foam mulched by passing once through modified Reinco Model TM 7-30 hay spreader.

Foam mulch particle size distribution as determined by sifting through square mesh screens.

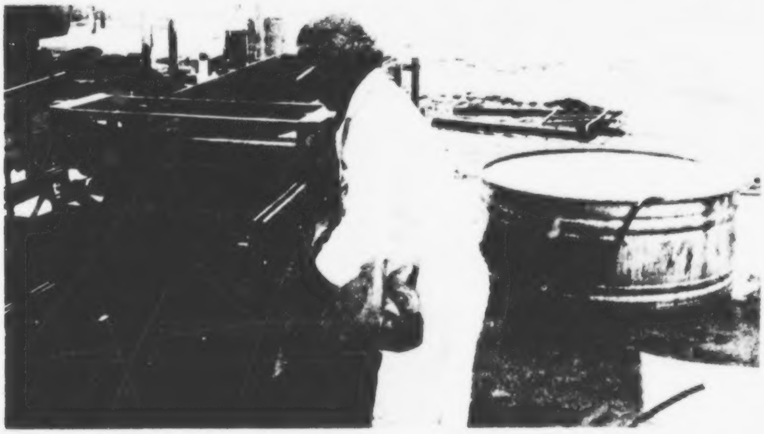
Screen Square Size	Cumulative Foam Retained (by Weight)
4" x 4"	0.7%
3" x 3"	16.4%
2" x 2"	60.5%
1" x 1"	94.7%
1/2" x 1/2"	98.7%



a) Foam Mulch Application



b) Sorbent Draining



c) Wringing of Foam

Figure 35 - APPARATUS AND PROCEDURES

TABLE 13

PROCEDURES USED FOR SORPTION TESTS IN LARGE TANK

Equipment

1. A 5-ft diameter 3-ft deep circular thin walled tank
2. A 6-ft diameter, 3-ft deep circular thin walled tank
3. 1/4-inch mesh minnow net
4. Mulched foam
5. Roller wringer
6. One 1000 ml graduated cylinder
7. Tretolite C-10 demulsifier
8. A triple beam balance
9. A hanging scale, 20 lb capacity

Procedure

1. Place 5-ft diameter tank within 6-ft diameter tank
2. Fill inside tank with water
3. Place net in the water with edges out
4. Add a measured amount of oil
5. Weigh the mulched foam
6. Place foam on slick and start the stop watch simultaneously
7. Pull the foam out with the net at proper time (usually after two minutes soaking time) and let drain for desired period (usually 30 seconds)
8. Hang on scale and weigh
9. Use Oil Herder© to surround the slick left in the tank
10. Skim all the oil off the surface
11. Separate the oil and water recovered
12. Use C-10 demulsifier to separate the emulsion (if any)
13. Measure the total amounts of oil and water recovered
14. Calculate amount of oil absorbed by the foam, allowing for residual in tank
15. Roller wringer is used to recover the oil from the foam

Environmental Conditions

Wringer tests - outdoors, 70°F
Weight tests - indoors, 72°F
No agitation

The results of these experiments for the second cycle are illustrated in Figures 36 and 37. To aid in the interpretation of these and later results, the foam, applied on the water surface in the 5-foot diameter tank in various area concentrations, is shown in Figure 38. As shown in Figure 36 the total effluent volume and oil volume sorbed per unit mass of foam decrease monotonically with increasing concentration of sorbent application. The fractional oil content of the effluent by volume decreased with increasing concentration of sorbent application as shown in Figure 37. Also included in Figure 37 is a plot of the quantity of oil recovered per unit surface area of slick as a function of the area concentration of the sorbent. This curve was obtained by multiplying points of the smoothed specific oil sorption curve in Figure 36 by the corresponding concentrations of foam mulch. It should be noted that the curve represents only the oil recovered from the foam by the squeezing process and does not account for that which remains within the foam matrix after wringing. The upper barrier in Figure 37 represents the maximum oil available per unit area of the 0.06 in. slick. The maximum portion of the oil is recovered at about 0.063 lb/ft^2 sorbent concentration, and corresponds to about 65% of that which is available within the slick. In considering this result, it should also be noted that the specific fluid volume and oil volume recovered, and the percent by volume oil content of the effluent, all show increasing trends as functions of the number of cycles through which the oil sorbent is processed, and thus the shape of the curves of Figure 37 will be altered for subsequent cycles.

To eliminate the effect of foam handling and influence of inefficiencies of the wringing process, further experiments were conducted in which the quantity of oil removed from the slick was measured directly by skimming the tank after the foam was removed and subtracting the quantity of oil remaining from that originally contained in the slick. In each test a given sample of foam was used only once, though both dry sorbent and sorbent which has been presoaked in oil and wrung "dry" were used in different tests. The fluid which drained from the sorbent when it was lifted from the tank was examined and found to contain little or no oil. The results of these tests are shown in Figures 39 through 41. Figure 39 shows the quantity of oil removed from the slick as a percentage of that available.

Performance was better for the dry foam than for that which was oil presoaked. Specific oil sorption by the foam is shown in Figure 40 and is seen to decrease with increasing areal concentration of foam due to the rapid decrease in the specific rate of sorption of oil by the foam as the increasing number of particles rob one another of available oil and cause a rapid decrease in the thickness of the slick over the available soaking time. Again, performance is seen to be poorer for the presoaked foam. Finally, the concentration by volume of oil in the fluid contained within the foam matrix is shown in Figure 41, and is seen to deteriorate steadily for increasing areal concentration of application. Again, dry foam exhibits superior performance.

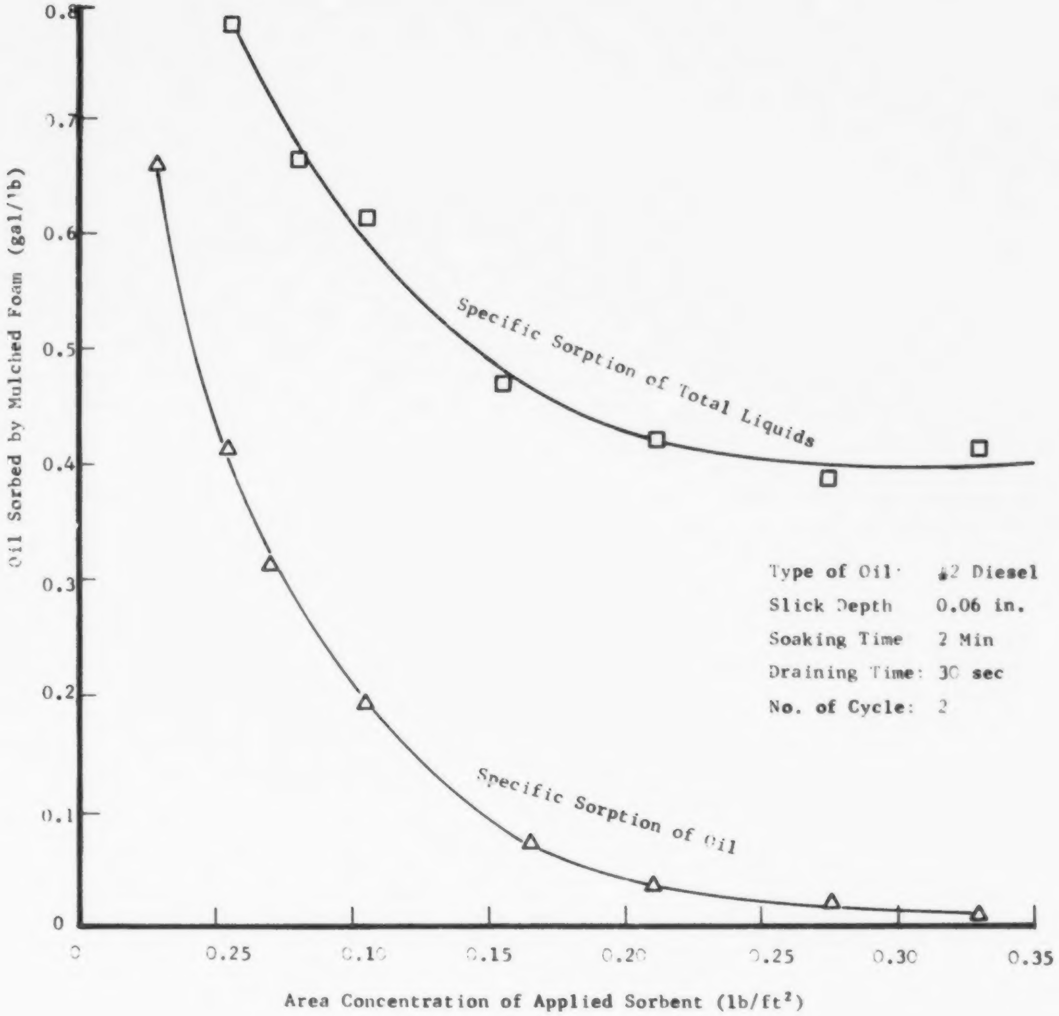


FIGURE 36 - SPECIFIC SORPTION OF FLUIDS AS A FUNCTION OF THE AREA CONCENTRATION OF FOAM SORBENT

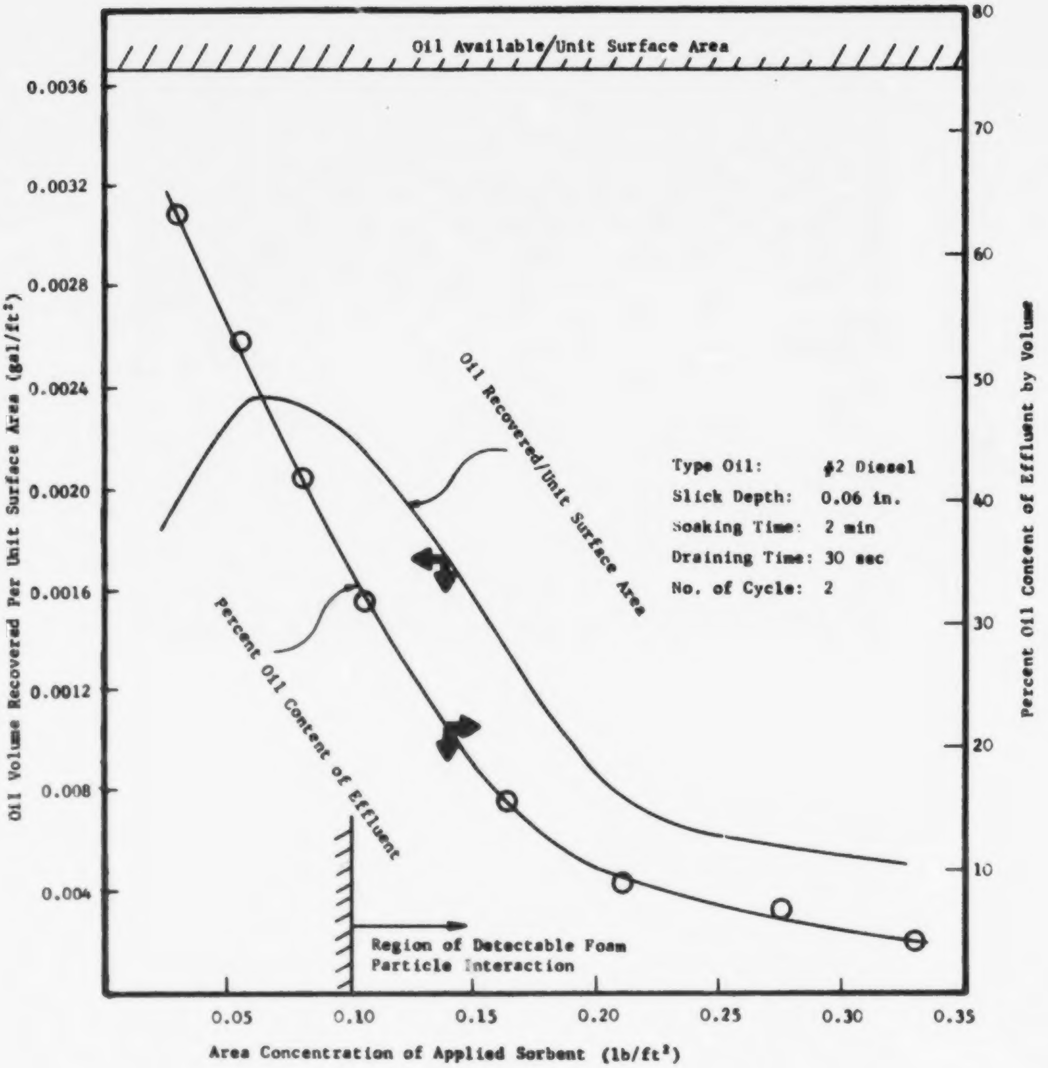
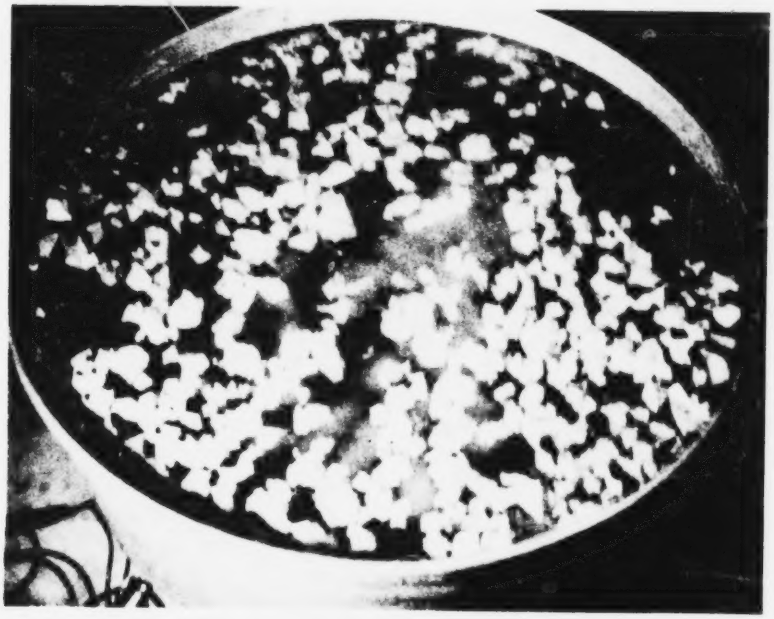
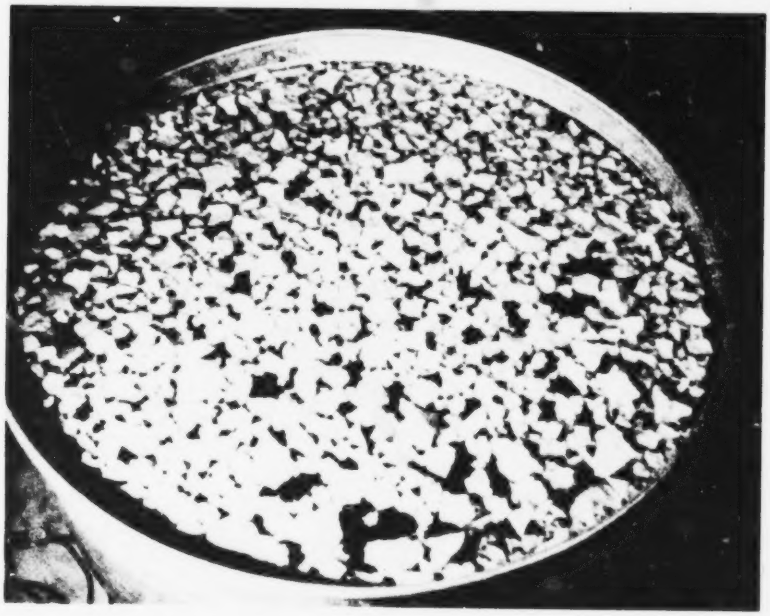


FIGURE 37 - OIL RECOVERED PER UNIT AREA OF SLICK AND EFFLUENT PURITY AS FUNCTIONS OF AREA CONCENTRATION OF FOAM SORBENT APPLICATION

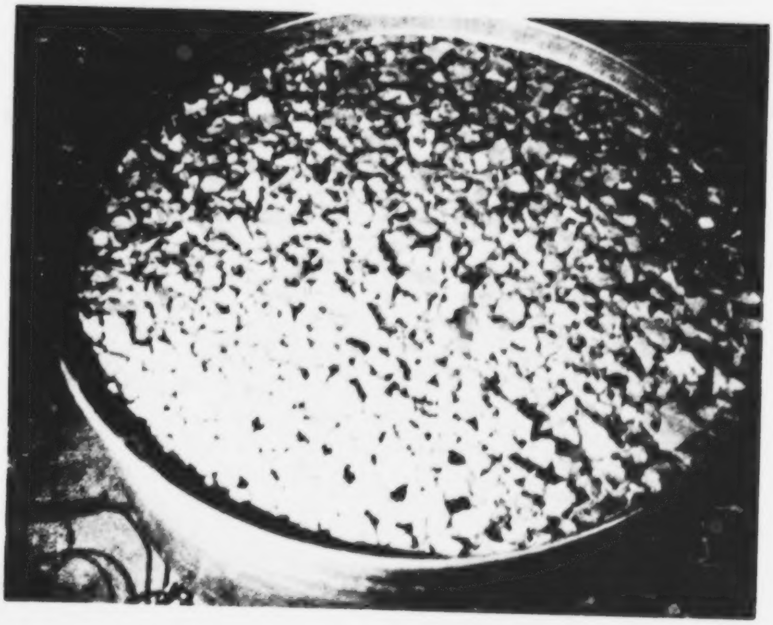


a) Area concentration = 0.06 lb/ft^2

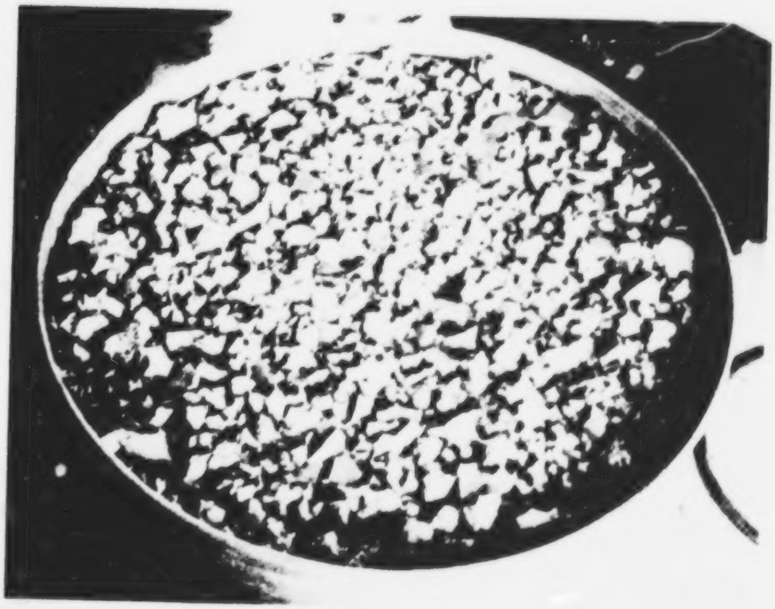


b) Area concentration = 0.12 lb/ft^2

Figure 38 - MULCHED POLYURETHANE FOAM ON SURFACE OF 5-FOOT DIAMETER TANK



c) Area concentration = 0.2 lb/ft^2



d) Area concentration = 0.28 lb/ft^2

Figure 38 (Continued)

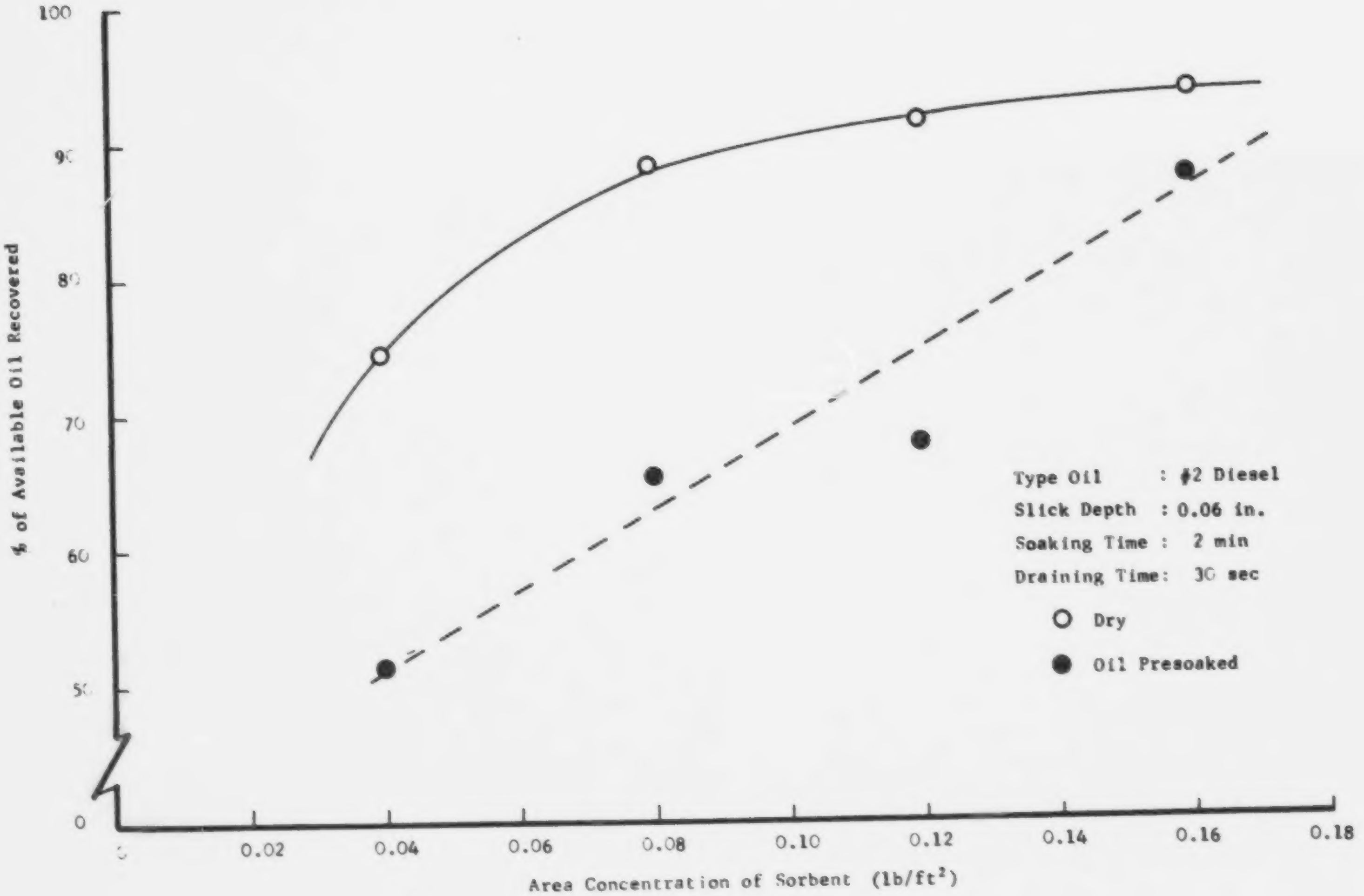


FIGURE 39 - OIL REMOVED FROM THE SLICK AS FUNCTION OF AREA CONCENTRATION OF FOAM SORBENT

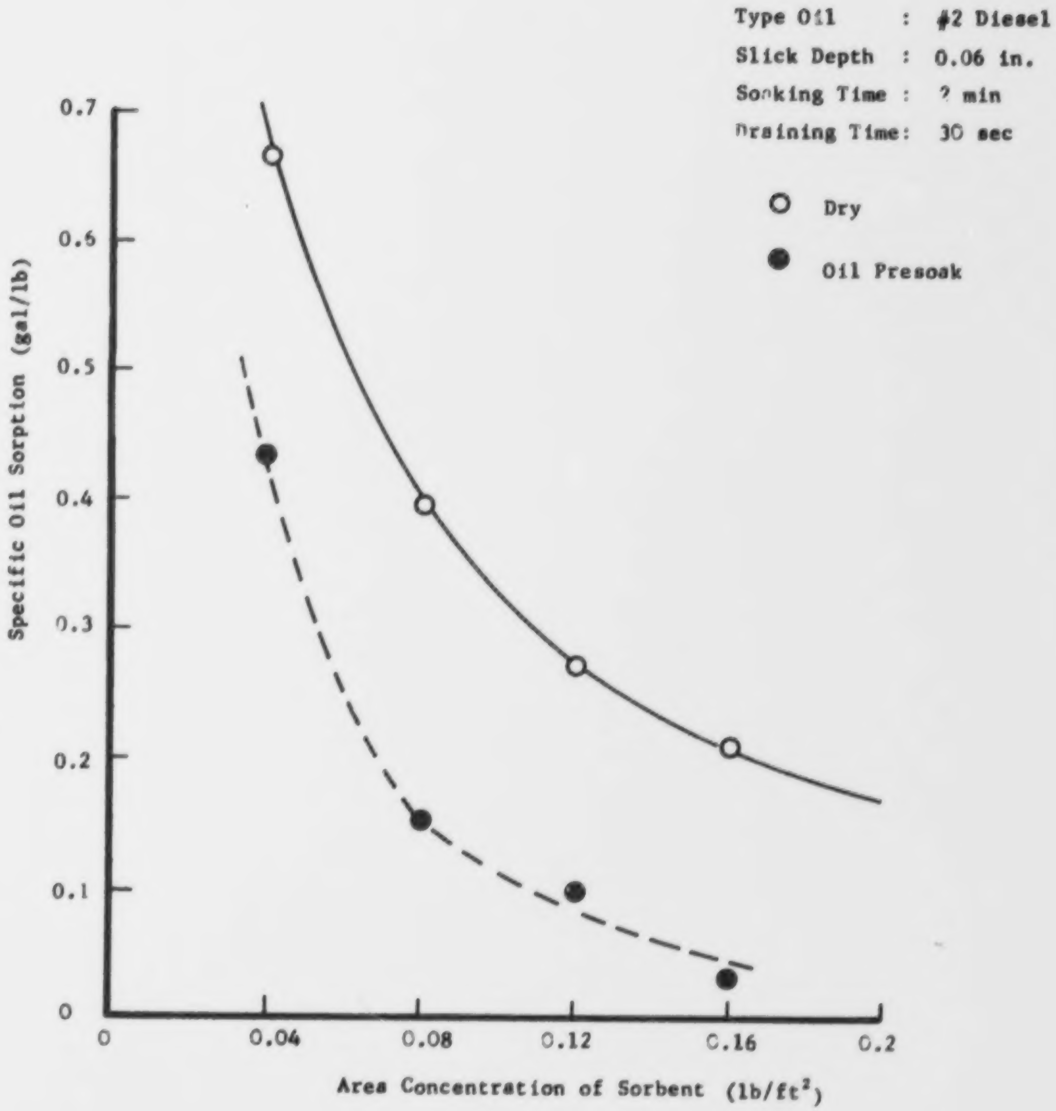


FIGURE 40 - SPECIFIC OIL SORPTION AS FUNCTION OF AREA CONCENTRATION OF FOAM SORBENT

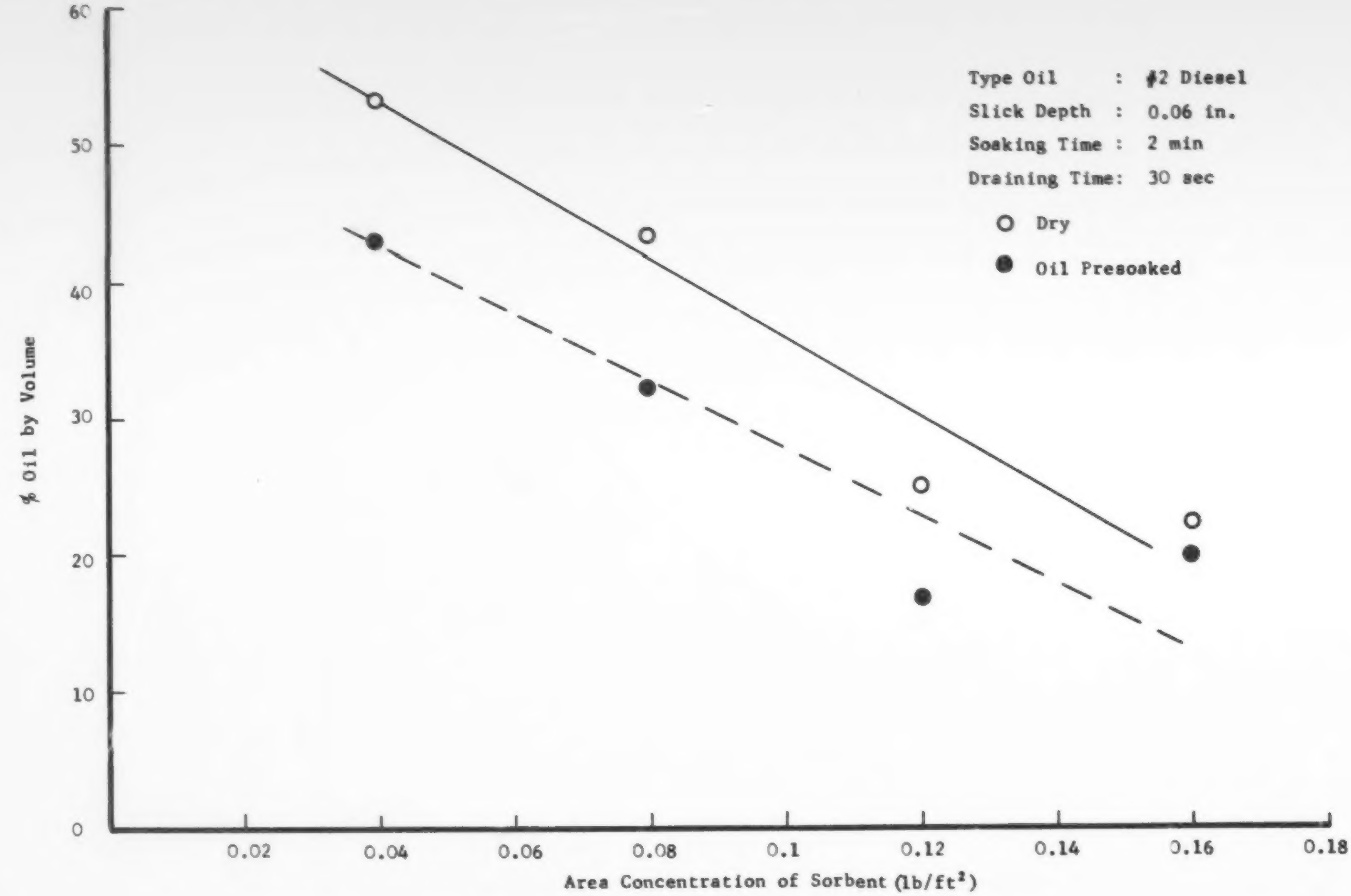


FIGURE 41 - OIL CONTENT OF NET INFLUENT AS FUNCTION OF AREA CONCENTRATION ON FOAM SORBENT

Once probable soaking and draining times had been established for the proposed full-scale sorbent recovery system, further experiments of the nature of those above were conducted with a soaking time of one minute and draining time of 10 seconds. For these experiments, No. 2 Diesel Oil and Carnea 21 were selected as the test oils. Carnea 21 was selected as the earlier bench-scale work had demonstrated specific sorption and effluent oil contents for this oil to be near the minimum for the various available oils tested.

Results of these tests are presented in Figures 42 through 49. Experiments were again run with sorbent which had previously been soaked with oil and wrung dry. Results of this work, for a 0.06 in. deep slick, are shown in the figures as solid data points and broken lines. From these figures it may be seen that performance again generally deteriorates as slick depth decreases. In general, little improvement in efficiency is seen to be achieved for sorbent application concentrations over about 0.1 lb/ft^2 in Figures 44 through 46. At these application concentrations, Figures 41 and 42 indicate that a specific oil sorption of two or better may generally be expected for 0.06 in. slicks. Figures 41 and 42 demonstrate that the effluent oil content under these conditions ranges from about 20% to 45%. These figures provided the basis for performance estimates of the on-barge, full-scale, sorbent recovery system (see Section XIV).

Compared to the results of previous experiments conducted at this laboratory and by others (e.g., see References 2 and 4) the specific oil sorption realized above may appear unduly conservative. However, the test conditions used here differed considerably from those used by others. The primary difference is the oil layer thickness adjacent to each piece of sorbent. For the data reported in References 2 and 4, the oil layer thickness was either very great (when measuring maximum sorption capacity) or was maintained constant during the test period, which corresponds roughly to very low areal coverage of the slick by foam. For the data reported in the present section of this report, the oil layer thickness adjacent to the foam pieces decreased during the course of the experiment, which means that total oil sorption was limited (among other things) by the rate of migration of the thin layer of oil on the water surface. This corresponds roughly (or actually) to high areal coverage of the slick by foam. The results presented in this portion of this report are felt to be realistic, lending themselves to the design of a practical oil recovery system of reasonable size.

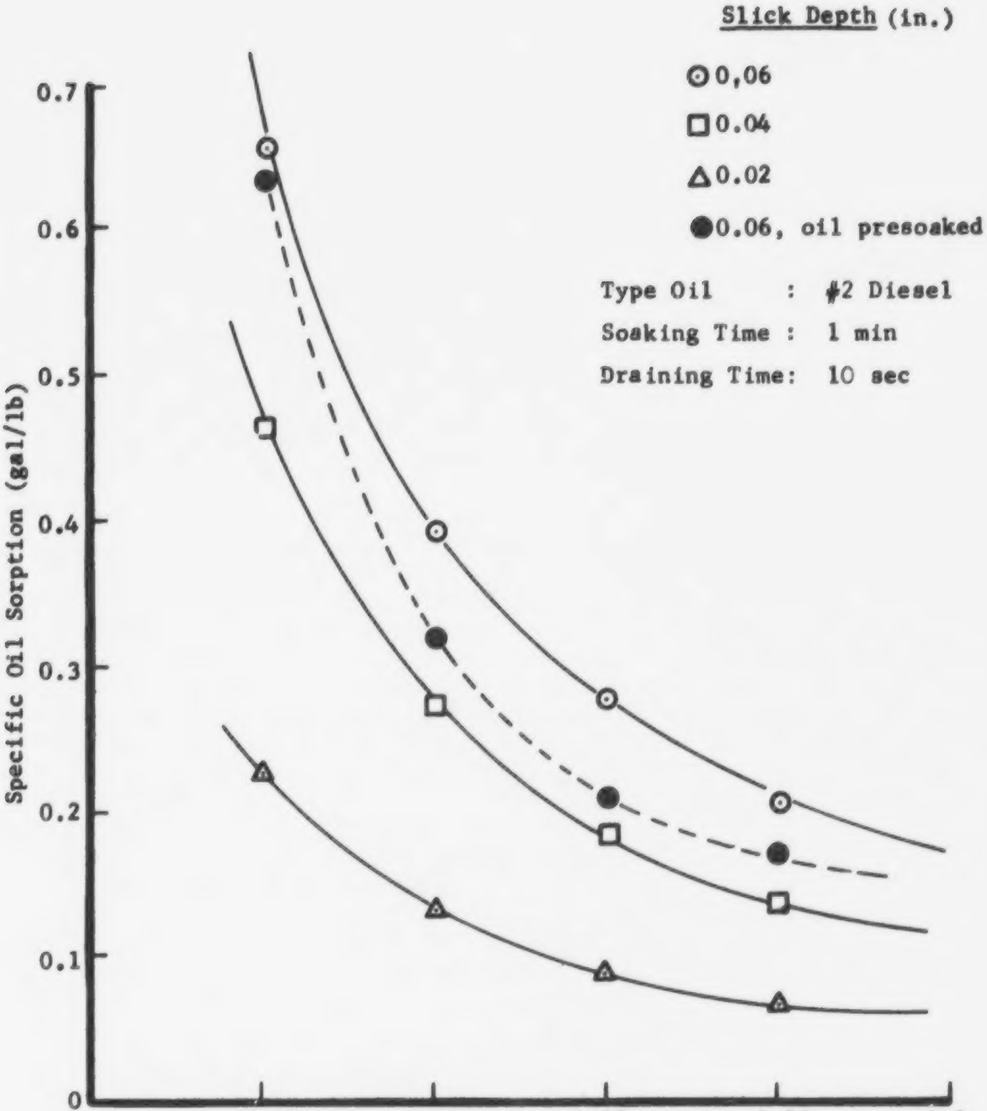


FIGURE 42 - EFFECT OF SORBENT APPLICATION CONCENTRATION ON SPECIFIC SORPTION OF OIL FOR NO. 2 DIESEL OIL

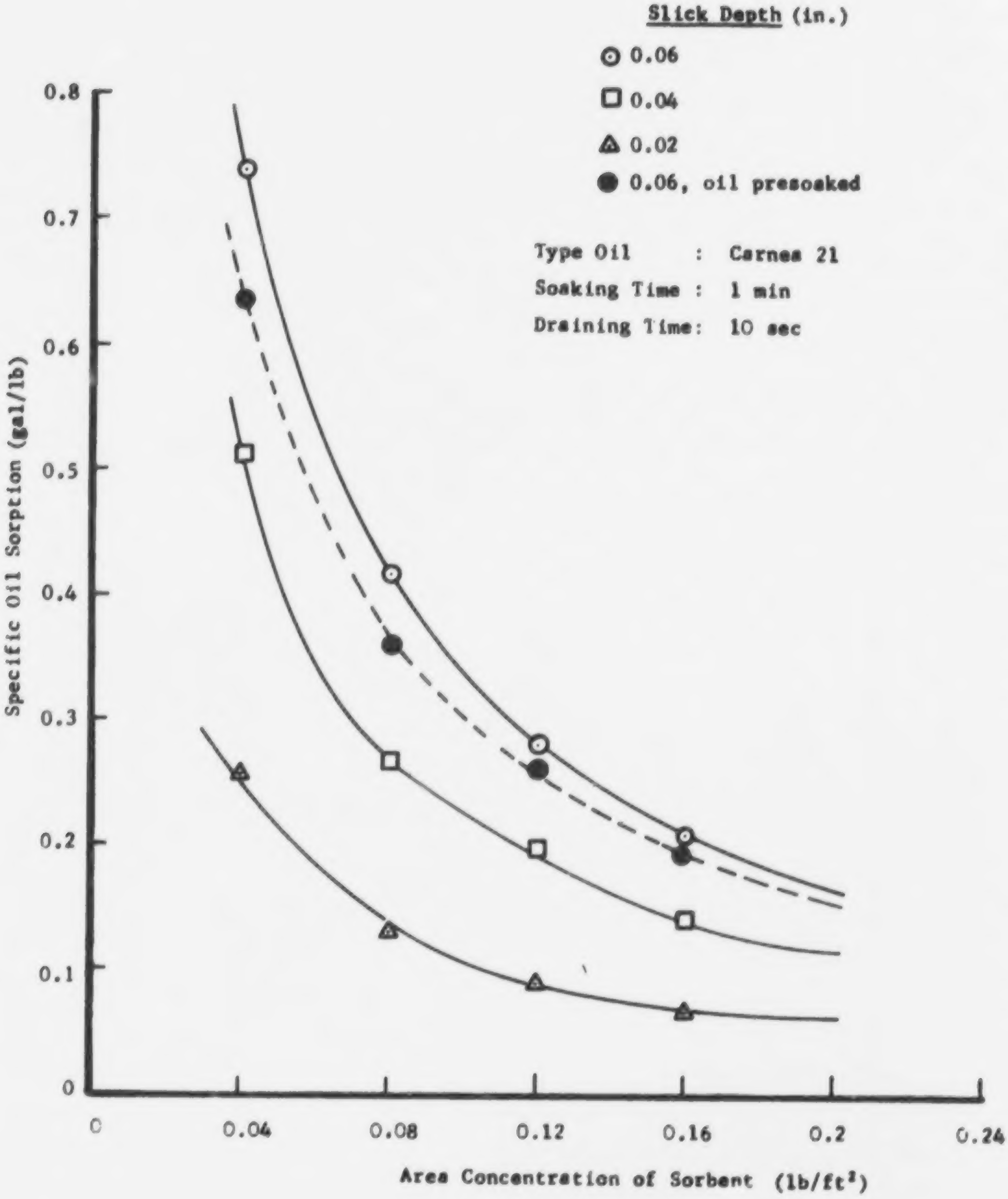


FIGURE 43 - EFFECT OF SORBENT APPLICATION CONCENTRATION ON SPECIFIC SORPTION OF OIL FOR CARNEA 21

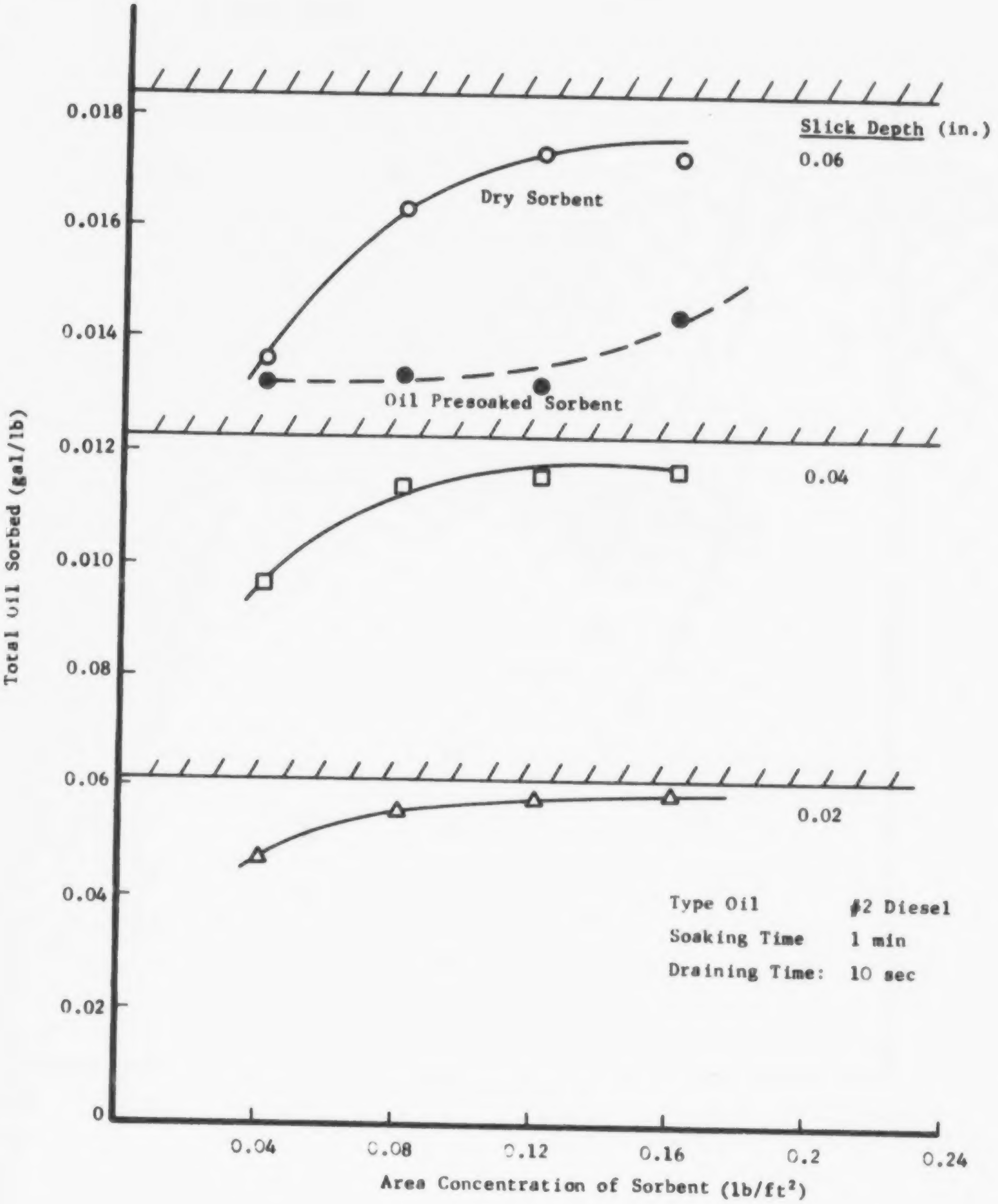


FIGURE 44 - EFFECT OF SORBENT CONCENTRATION ON RECOVERY EFFECTIVENESS FOR NO. 2 DIESEL OIL

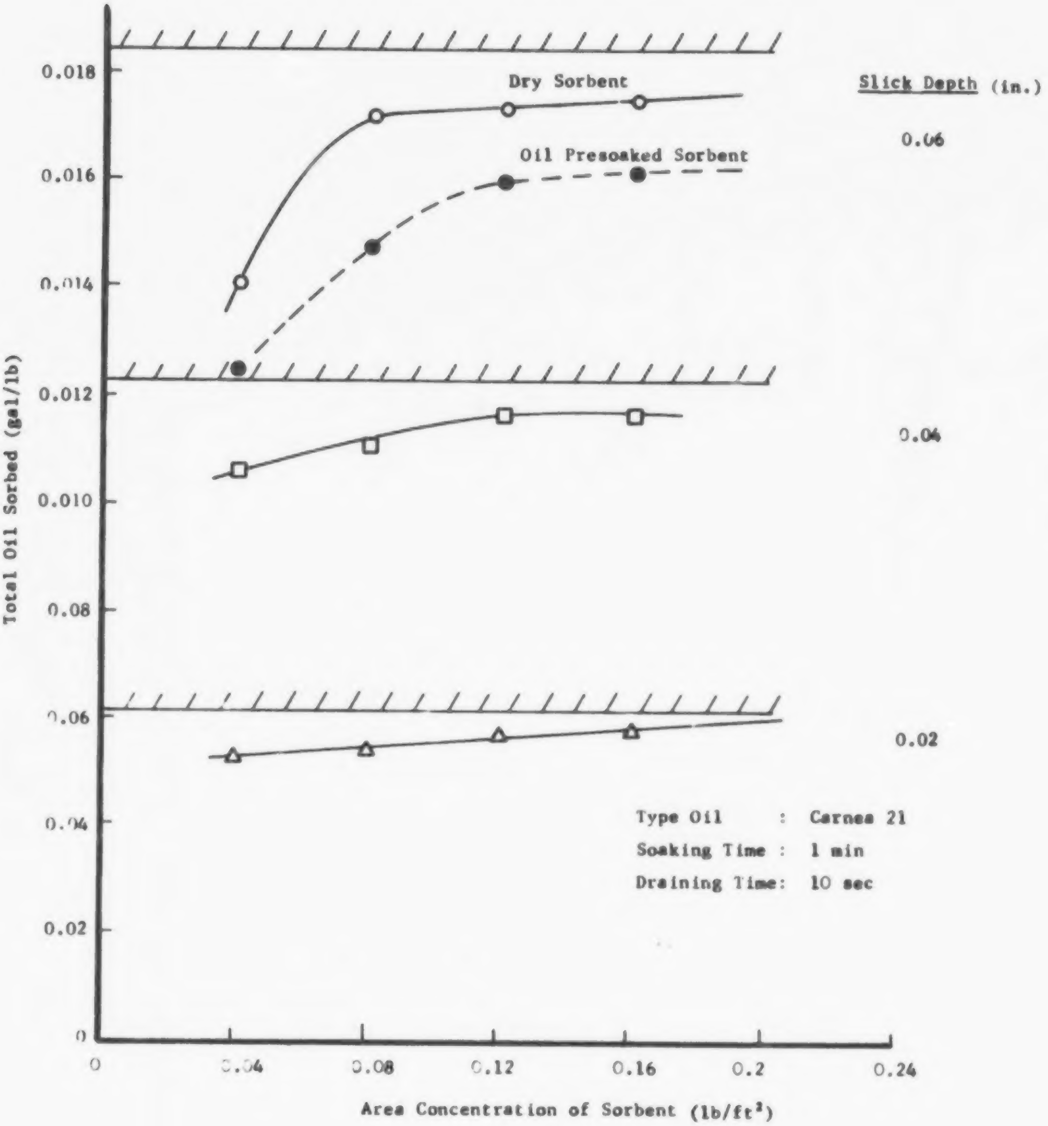


FIGURE 45 - EFFECT OF SORBENT CONCENTRATION ON RECOVERY EFFECTIVENESS FOR CARNEA 21

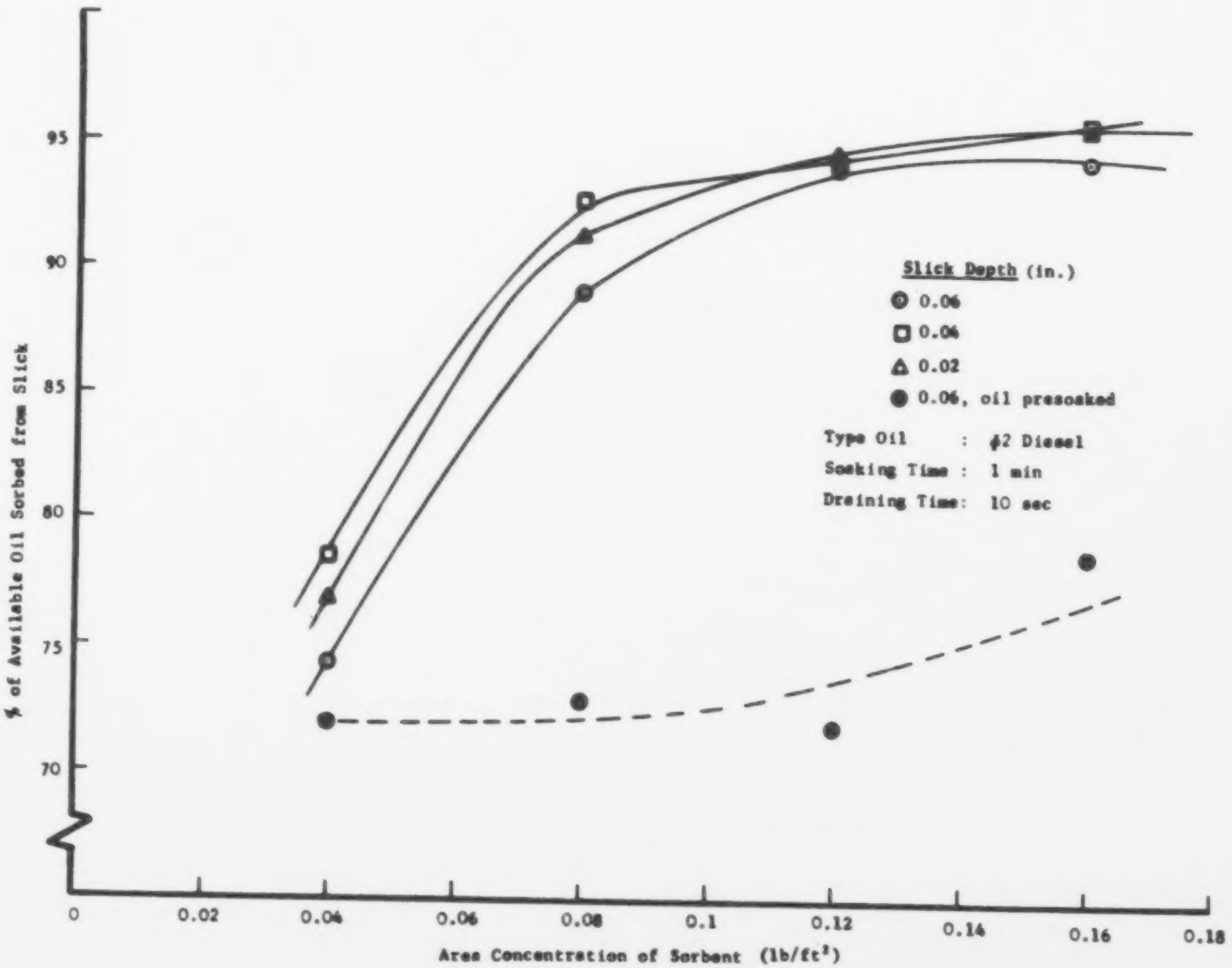


FIGURE 46 - EFFECT OF SORBENT APPLICATION CONCENTRATION ON RECOVERY EFFECTIVENESS FOR NO. 2 DIESEL OIL

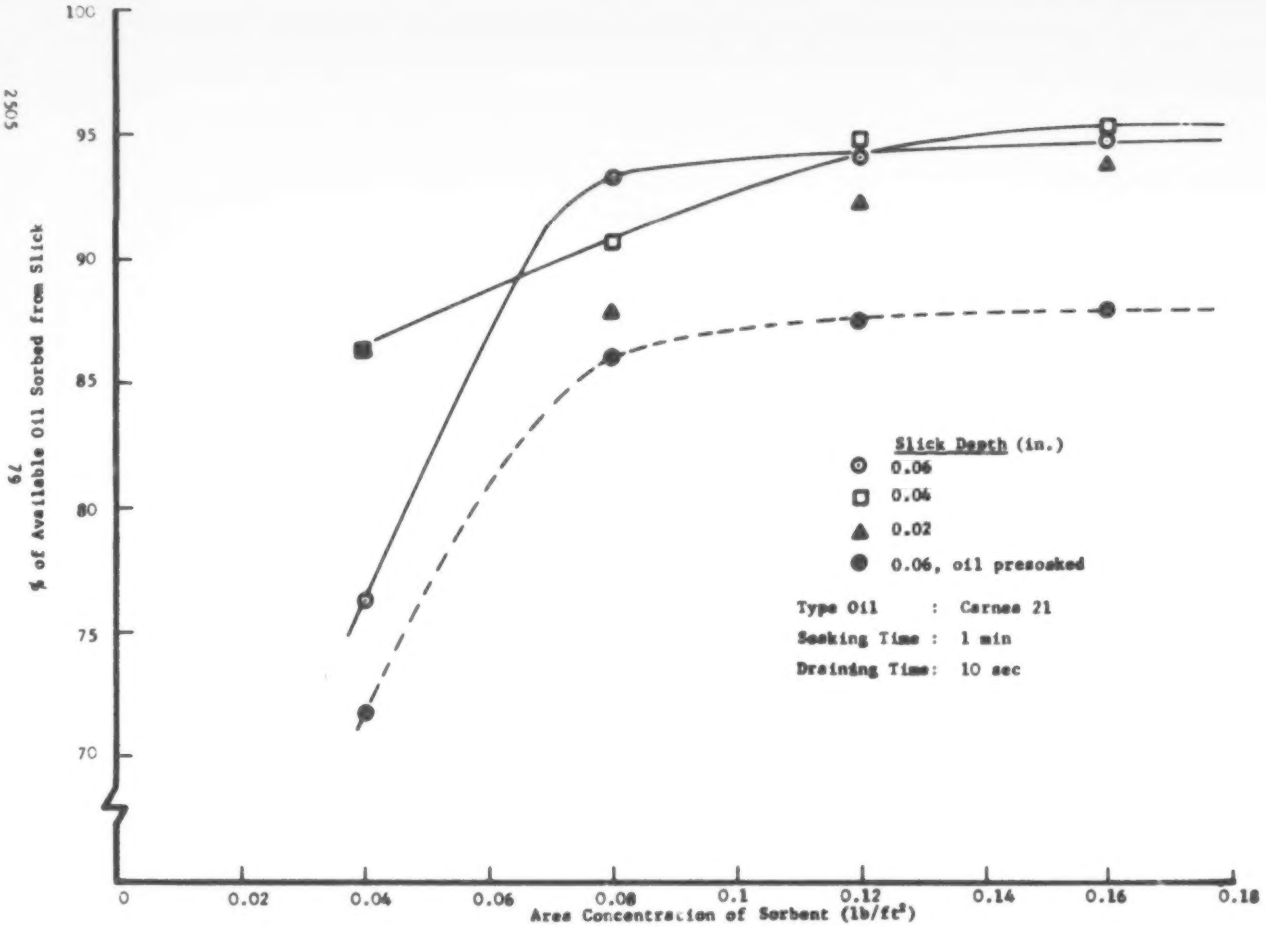


FIGURE 47 - EFFECT OF SORBENT APPLICATION CONCENTRATION ON RECOVERY EFFECTIVENESS FOR CARNEA 21

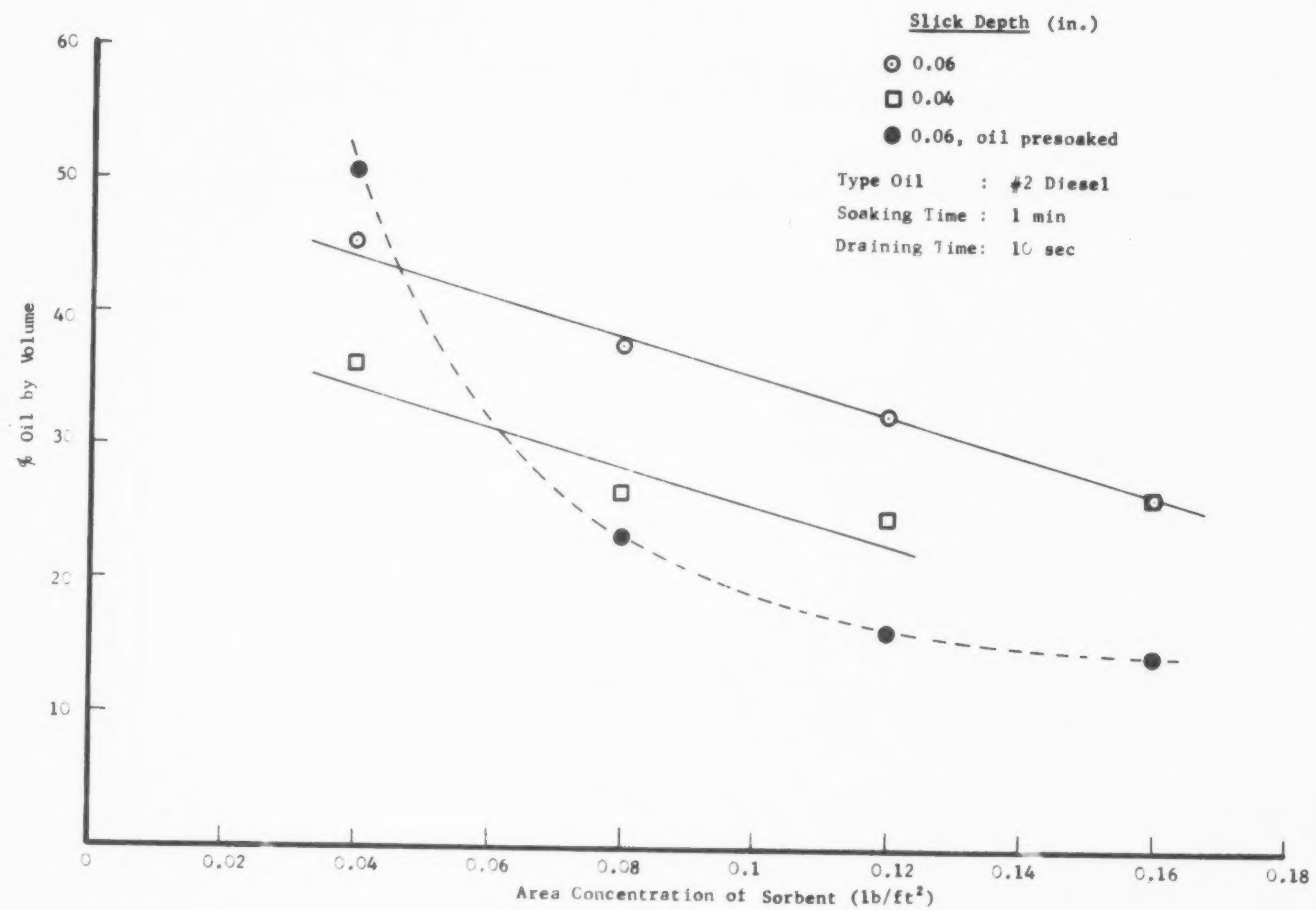


FIGURE 48 - EFFECT OF SORBENT APPLICATION CONCENTRATION ON OIL CONTENT OF AFFLUENT FOR NO. 2 DIESEL OIL

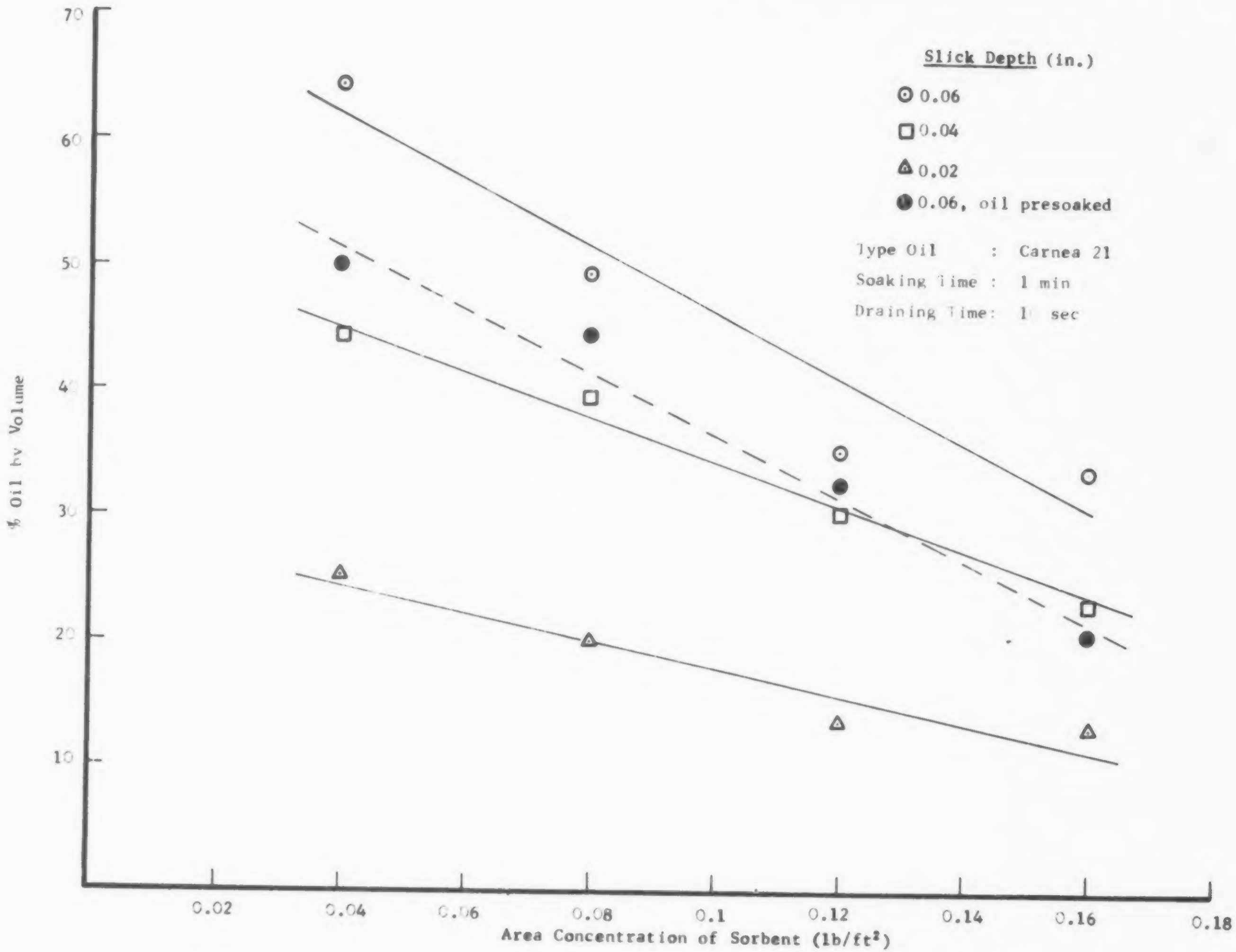


FIGURE 49 - EFFECT OF SORBENT APPLICATION CONCENTRATION ON OIL CONTENT OF AFFLUENT FOR CARNEA 21

SECTION VIII

DISTRIBUTION OF SORBENT

Introduction

The distribution and transport of the polyurethane foam begins with the cured foam bun and ends as the used foam is either redistributed or is stored for disposal. Foam buns are prepared by slicing or tearing prior to being placed in contact with the oil. For the transport of used foam from point to point, either belt conveyors or pneumatic pressure conveyors can be used.

Foam Preparation Requirements

The polyurethane foam generated on-site is produced as a bun (see Section VI). As presently made, the buns have an impermeable skin of closed cells formed on the upper surface during curing. The lower surface which forms in contact with a substrate of paper or other material, is largely open-celled. To increase efficiency as a sorbent, the bun is torn or sliced in a way that will expose the open cells in the interior of the bun. Ideally, these pieces should be as small as can effectively be recovered from the water. A particle size distribution which may be largely retained on a one-inch or larger square mesh appears practical. Two methods of foam preparation have been considered in this study.

Slicing or Breaking

A sample of our foam bun was delivered to one machinery manufacturer (the Fitzgerald Company) for a factory evaluation using a standard breaking machine such as used in the food and drug industry. It was found that the particular machine produced a particle judged to be well suited to oil spill work. The pieces were relatively uniform in thickness (3/8-in. to 1/2-in.) and of a size easily recovered (see Table 14 and Figure 50). A sieve analysis of this material is reported

TABLE 14

PARTICLE SIZE DISTRIBUTION
OF SLICED FOAM

Screen Square Size	Cumulative Percent Foam Retained (by weight)
4-in. x 4-in.	22
3-in. x 3-in.	44
2-in. x 2-in.	55
1-in. x 1-in.	82
< 1	100

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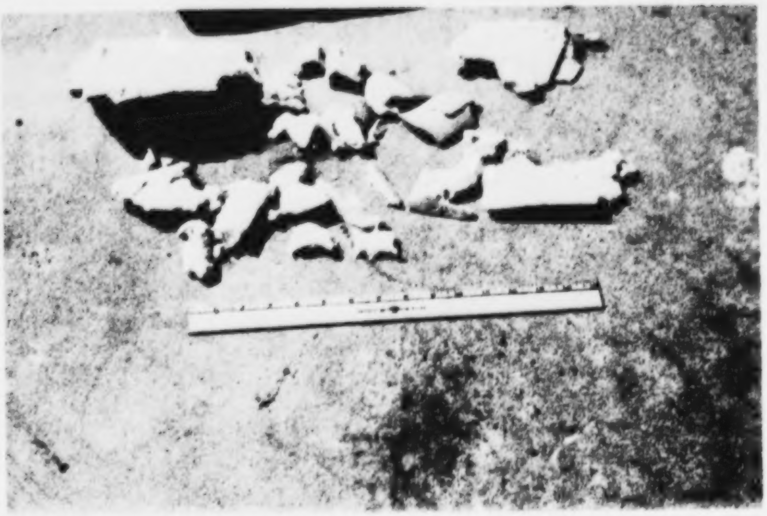

Figure 50 - FOAM PREPARED WITH FITZGERALD BREAKER

in Table 14. This machine is not considered practical for offshore use in its present form, requiring major modification or redesign for adaptation to this service and to increase its capacity. Although it might be considered for future development, no further work was attempted in this study.

Mulching

Foam generated on-site is characteristically of relatively low tensile strength, making it possible to tear or break the buns into suitable pieces with a common power mulcher such as is manufactured by Reinco of Plainfield, New Jersey (Figure 51). In the standard configuration, control of the particle size is not completely satisfactory, and it was found that the addition of studs (or shredder bars) to the beater chamber improved performance, as illustrated in Figure 52. This simple field modification could be made on any of the several hundred similar machines now in use. A typical particle size distribution, as obtained with our modified Reinco Model TM 7-30 mulcher, is shown in Table 12. For this study, a total of

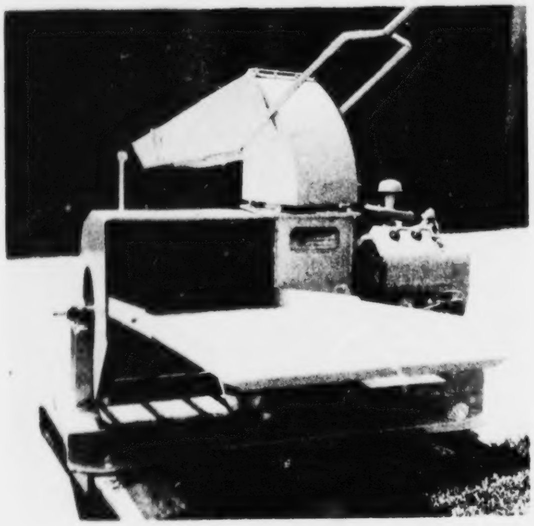

Figure 51 - REINCO TM 7-30 POWER MULCHER

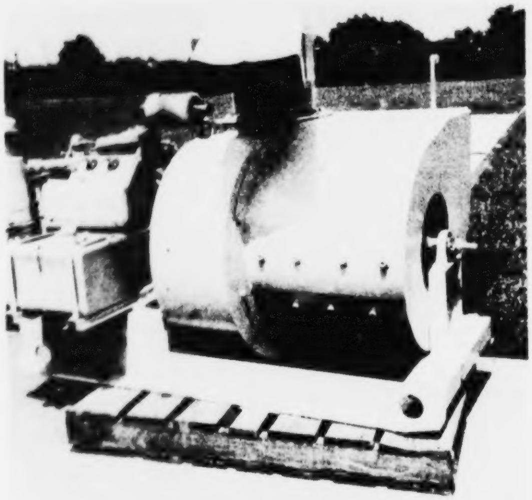

Figure 52 - MODIFICATION TO MULCHER

eleven 1/2-in. diameter studs, projecting 2-1/2-in. into the beater chamber, were installed.

Distribution of New Foam

The initial distribution of fresh foam is easily accomplished with the power mulcher or, if the foam is already mulched, by a simple centrifugal blower.

The small Reinco TM 7-30 mulcher is manually fed and is capable of discharging foam at velocities approaching 150 mph (5000 CFM air stream). The unit is rated at four tons of baled straw per hour, but with foam in buns its rate is less due to the lower density of the bun. A mechanical feed or an enlarged chute would be a desirable modification for any machine purchased for this service.

In tests with the standard mulcher, manned by three men, small buns weighing five to six pounds were mulched at a rate of 2100 lb/hr. This rate can be increased by about 50% if buns are pre-sized to the width of the charging chute and of considerable length (say, ten feet). A further increase in rate (and increased safety) would be obtained by adding a long charging chute with high sides. However, 3000 lb/hr is a reasonable and conservative average rate. When fed to the mulcher as buns approximately 10-ft x 2-ft x 4-inches, the foam was distributed into a five to seven-knot wind to a distance of about 35 feet. When distributed downwind the maximum distance about doubled. In a typical experiment, the foam was mulched and blown to cover an area about 30 feet in diameter, the center of which was 45 feet from the spreader. Time required to cover the 30-foot diameter area was 15 seconds.

Another larger mulcher from the same manufacturer (Model M60-F6) has a larger charging chute and is rated at nine tons of straw per hour. Such a unit should be capable of handling over 6000 lbs of foam per hour.

Recycling of Foam

In the present concept, essentially all of the foam will be recycled after wringing. During recycling, the foam will contain enough residual liquid to raise the actual density to about 10 lb/ft^3. We have found that this foam, loosely piled, without mechanical compaction, occupies about 0.56 to 0.67 ft^3/lb dry weight equivalent. An average "apparent density" of 1.64 lb/ft^3 (dry weight equivalent) has been used for design estimates. Depending upon the size of the recovery system the handling of this foam for recycling may be by container, by belt conveyor, or by pneumatic systems.

Containers

If the foam is to be handled by batch methods, containers may be used. Fabric mesh bags, metal fabric bins, etc., might be utilized. Volume as well as package weight will be a significant limitation. A metal-fabric bin 6-ft x 8-ft x 12-ft might hold about 5500 lbs (or 1000 lbs dry weight equivalent), representing an oil-sorption capacity of from 350 to 700 gallons. Thus, it may be seen that this approach is best suited to small capacity systems or cases where the material must be transported over a considerable distance prior to redistribution. Such containers might be placed on the stern of a support boat, filled by blowing through a conduit then distributed by opening a tailgate.

Belt Conveyors

As the oil recovery process is continuous, components of the system will preferably provide for continuous flow. Belt conveyors of various types are well suited to this type of material handling situation, where the movement is confined to a single vessel. The conveyor can be extended a limited distance outboard for distributing the foam on the water.

Pneumatic Conveyors

The foam as recycled can readily be conveyed in a stream of air. Density, particle size, and the continuous nature of the process are all compatible with this system. In discussions with suppliers, it was estimated that for moving quantities of this material distances of at least 150 feet, a minimum air stream velocity of 3000 ft/min would be required. Conveying could be by use of a simple centrifugal blower or by a positive displacement blower with feed by air lock into the pressure side.

The latter type of system was investigated in discussions with one manufacturer, Fluidizer, Inc. A preliminary recommendation called for the following equipment to move 156,000 pounds of material/hr at least 150 feet, discharging into the atmosphere: 1 - 75 hp, electric motor dirven positive displacement blower (rated at 1200 CFM, 10 psi); four foam inlet hoppers; four rotary air lock injection valves; and an eight-inch transfer line. The system could be palletized for storage or shipment. The total system weight might be approximately nine tons, the maximum single pallet weight 5500 pounds, and the maximum dimension to be the height selected for the hoppers (which would be nested for storage). A system of this type would be well suited to use on a large vessel, provided adequate electrical power is available. A lighter, simpler system, perhaps better suited to use on smaller vessels would be the simpler blower. Preliminary estimates from one supplier suggested a 40 hp blower with lightweight pipe conduit.

In an attempt to evaluate the practicality of the blower concept, a series of simple tests were carried out using the mulcher as a blower (Figure 53). The results of these tests are shown in Table 15.

TABLE 15

FOAM TRANSPORT TESTS

Run*	Foam	Time	Rate
A-1	64 lb-wet	50 sec	4600 lb/hr
A-2	53 lb-wet	35 sec	5400 lb/hr
A-3	27-1/2 lb-wet	30 sec	3300 lb/hr
B-1	24 lb-dry	65 sec	1300 lb/hr
B-2	45-1/2 lb-wet	75 sec	2200 lb/hr
B-3	39-1/2 lb-wet	47 sec	3000 lb/hr
B-4	19-1/2 lb-dry	33 sec	2100 lb/hr

* A series: 50 feet of 16-inch conduit
B series: 98 feet of 16-inch conduit

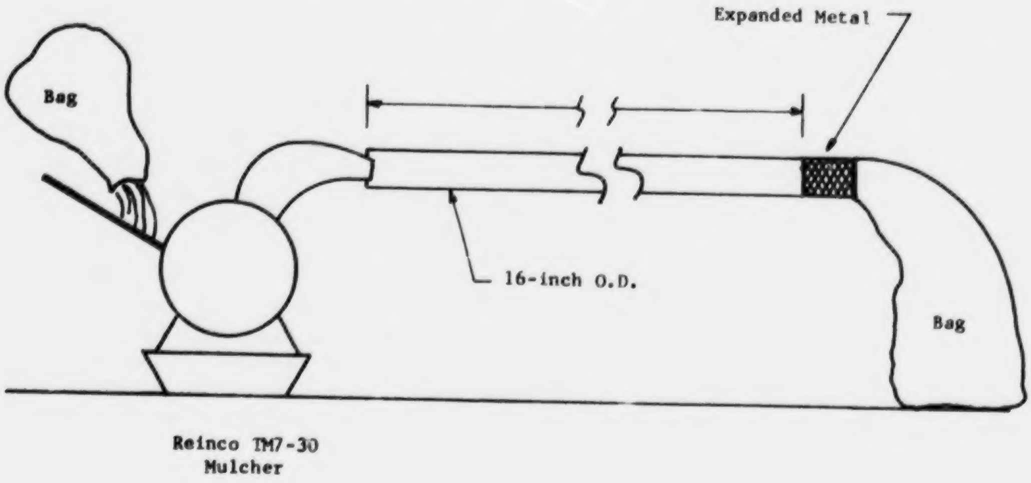
Expanded Metal
Bag
16-inch O.D.
Bag
Reinco TM7-30
Mulcher

Figure 53 - FOAM TRANSPORT TEST USING POWER MULCHER

Pre-mulched foam was collected in large bags. For the wet foam tests the foam was water saturated, wrung with three passes through the model wringer (see Section XI) and then rebagged. For these tests the foam was remulched in passing through the mulcher, as the beater chains and studs were not removed. A discharge conduit of 16-inch pipe was selected on the basis of the rated blower capacity of 5000 CFM, though a flow slightly below the desired 3000 ft/min was achieved against the back pressure. By repeated observation of single particles, an average particle velocity (in Test B-3) of about 2500 ft/min was recorded.

In no case did it appear that the blower was overloaded, although during surges in the manual feeding foam remained in the beater chamber longer than usual. The manual feed operation, which involved dumping premulched foam from bags into the standard chute, limited throughput. A suitable hopper or an enlarged chute might double the throughput.

After the second pass through the mulcher and into and out of the system, some size degradation was observed, possibly due to minor losses in the actual handling of the foam. This degradation was more pronounced in the "B" series, (see Table 15) and is shown in Table 16. (See also Section XII of this report).

TABLE 16

PARTICLE SIZE DISTRIBUTION
RETAINED ON SCREEN - %

	Single Mulch	Second Mulch and Transport	
Screen Size	Dry	Dry	Wet
4-in. x 4-in.	0.7	0	0
3-in. x 4-in.	15.7	< 0.2	< 0.2
2-in. x 2-in.	44.1	32.5	29.0
1-in. x 1-in.	34.2	65.1	69.0
< 1-in.	5.3	2.2±	2.0±

Pneumatic transfer of foam during recycling appears to be the preferred method. However, further study is recommended, particularly with respect to the possible hazard from static charge accumulation, though this does not appear to be a significant hazard in a fully grounded system discharging into the open water (as opposed to discharging into a confined space such as a tank).

SECTION IX

COLLECTION

The proposed oil recovery system utilizes a one or two sided "V" shaped converging boom system to concentrate oil soaked sorbent at the harvesting location. Failure of these booms to contain the sorbent in the absence of waves will generally result from one of the two phenomena shown in Figure 54. In the case of Figure 54(a), the foam is simply swept beneath the boom by the rapid current and consequent steep pressure gradient along the vertical face. In the case of Figure 54(b), the gap between the converging booms becomes blocked in low currents by bridging of the foam particles, resulting in a pile up of foam against the boom, along which additional foam may roll when driven by the current.

To aid in developing an understanding of the behavior and flow of a sheet of mulched foam in proximity to oblique and converging booms, experiments were made to determine the linear shear strength of a sheet of the mulched polyurethane foam floating on water. The apparatus used for these experiments is illustrated in Figures 55 and 56. The cross-hatched test area in Figure 56 measured 3-ft 10-inches in width and 6-ft in length. The weight consisted of a container of sand. The test section was covered uniformly with foam mulch of the size distribution in Table 12, and sand slowly added to the weight until failure of the sheet was indicated by continuing movement of the floating baffles suspended from the longitudinal member connecting the two styrofoam floats (see Figure 56 and Table 17). The

TABLE 17

PROCEDURES FOR MEASURING SHEAR STRENGTH OF FOAM MULCH SHEET

Equipment

1. 15-ft x 4-ft x 2-ft tank with fabricated partitions
2. Mulched foam
3. Triple beam balance
4. 18-inch x 12-inch x 6-inch wax-coated styrofoam blocks
5. Weights

Procedure

1. Fill tank with water.
2. Place sliding partition in position and secure.
3. Weigh out desired amount of foam using triple beam balance.
4. Place foam in tank between partitions.
5. Pull on sliding partition by adding sand (weight) to the pulling mechanism until movement occurs.
6. Weigh the amount of sand that was required to cause movement.

Environmental Conditions

Indoors, 72°F.

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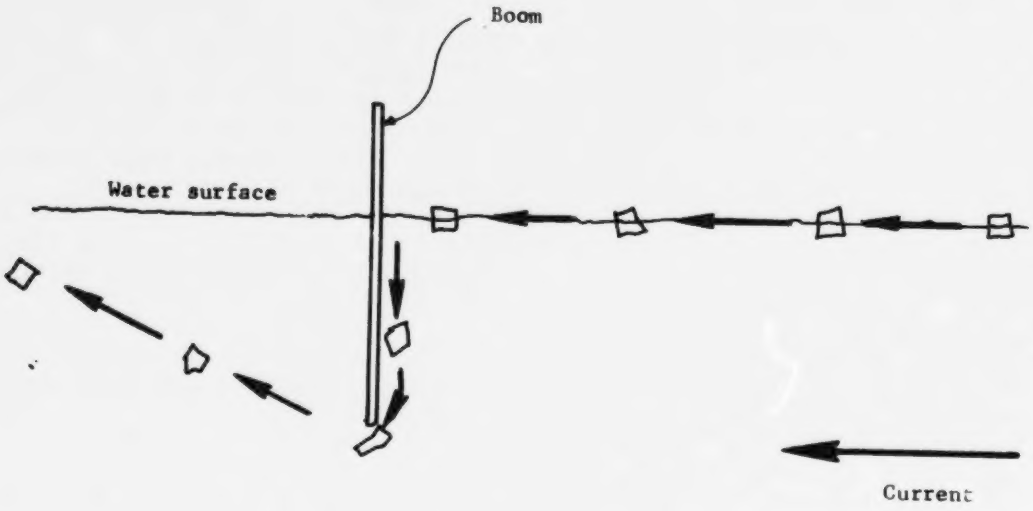
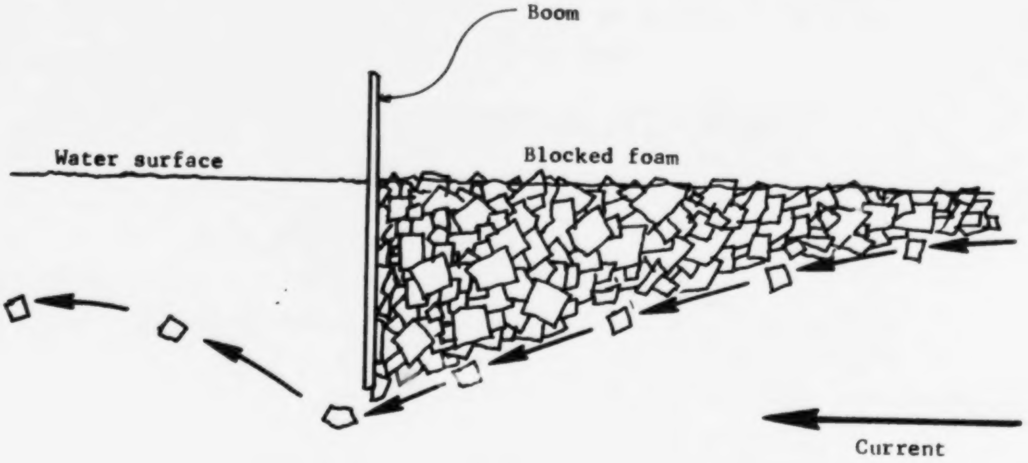

Boom
Water surface
Current

a) Foam sweeping under boom


Boom
Water surface
Blocked foam
Current

b) Foam rolling under boom

FIGURE 54 - TWO POSSIBLE MODES OF FAILURE FOR FOAM SORBENT BOOM IN ABSENCE OF WAVES

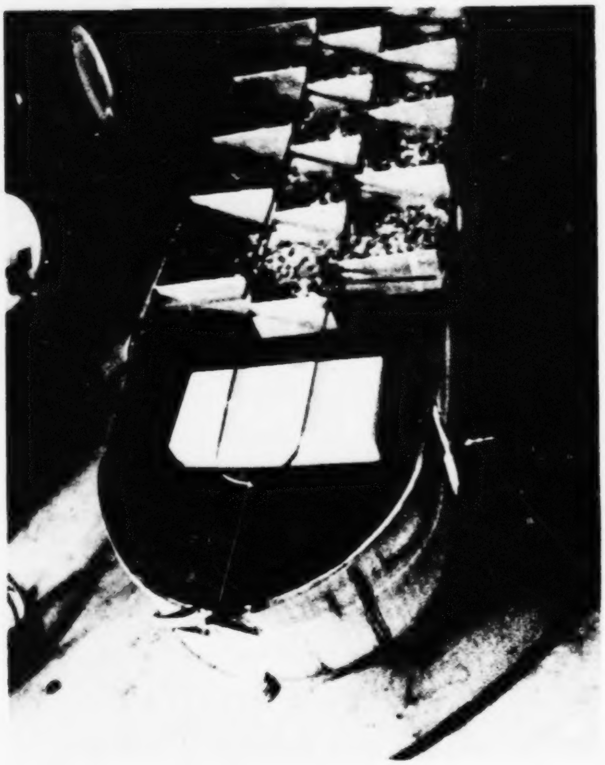


Figure 55 - SHEAR TEST APPARATUS IN USE

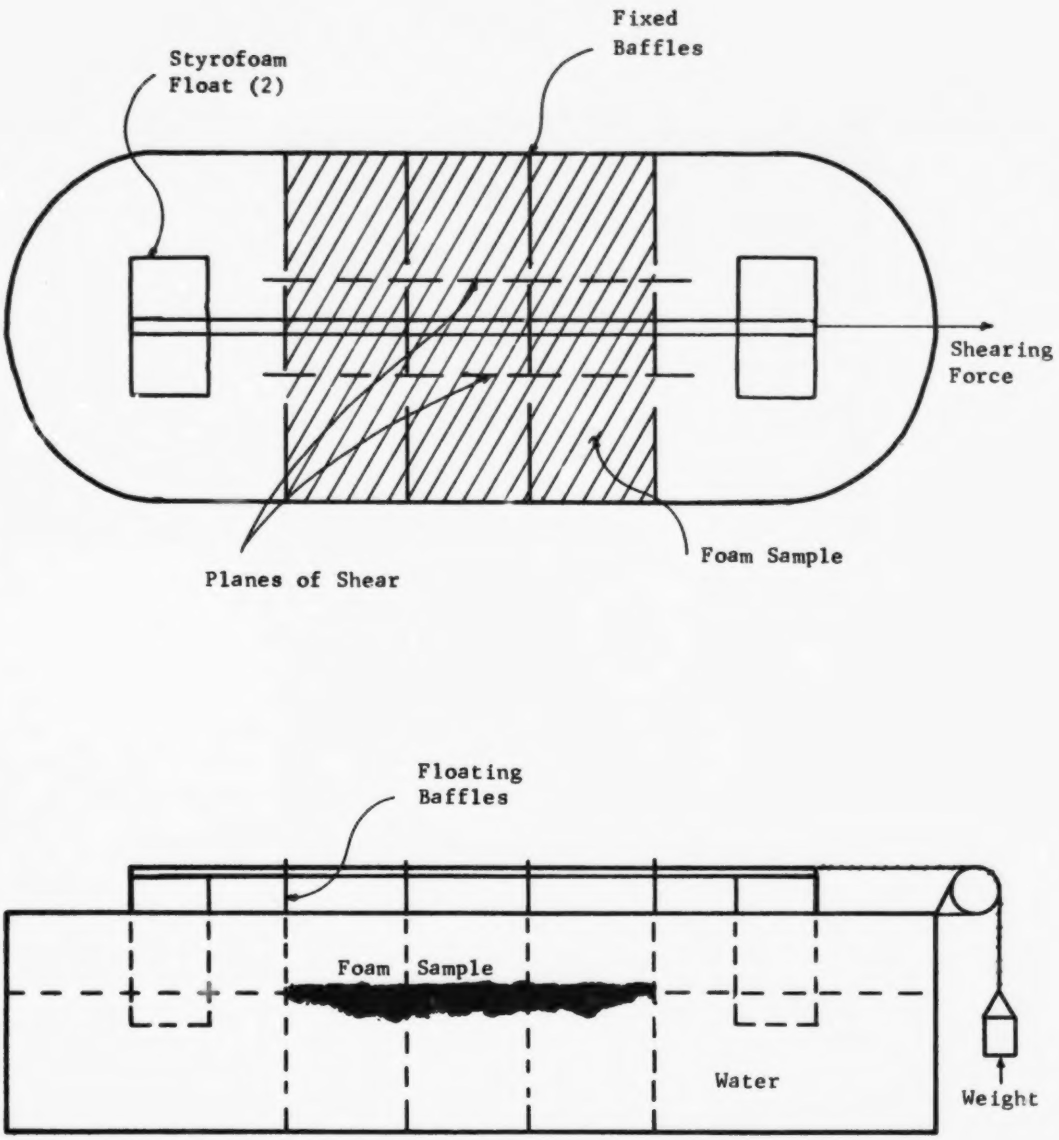

Fixed Baffles
Styrofoam Float (2)
Shearing Force
Planes of Shear
Foam Sample
Floating Baffles
Foam Sample
Water
Weight

FIGURE 56 - SHEAR TEST APPARATUS

results of these tests are shown in Figure 57, in which linear shear strength in lb/ft is plotted as a function of the area density of the foam sheet in lb/ft^2.

These data indicate that no stress can be supported by a foam sheet of an area concentration less than about 0.1 lb/ft^2. Above this value, stress may be supported by the sheet, and is seen to increase steadily with increasing foam concentration. This increase is due to both the increasing depth of the foam, resulting in a dilution of the stress over the vertical planes of shear, and increasing compaction, resulting from the weight of the foam above. This threshold concentration is above the shoulder of the oil recovery curves of Figures 46 and 47, and corresponds to the assumed application density of the sorbent for the system performance estimates (page 167).

The relationship of the maximum shear stress supportable by a foam mulch sheet to the blocking of converging booms during sorbent collection operations is illustrated in Figure 58. When blocking of the converging section occurs, the maximum shear stress lies in the vertical planes of the dashed lines at the gap edges. The probability of the occurrence of blocking is reduced for larger gaps as the fluid drag of a larger area of mulched foam must be supported along the lines of shear, resulting in higher shear stress for a given towing velocity and foam sheet length. The tendency of foam to bridge across the gap may also be reduced by decreasing the included angle between the booms, thus decreasing the normal pressure, and increasing the shear stress at the boom face, causing the foam to slip toward the gap more easily. The above data indicate that blocking cannot occur so long as foam concentrations in proximity of the gap are less than 0.1 lb/ft^2.

Large scale tank tests were run to determine the nature of the flow of foam mulch between the booms and bridging of the boom gap (see Tables 18 and 19). A pair of twelve-foot converging booms of 13-inch draft and 23-inch freeboard, positioned to form a 3-foot gap, were towed through foam mulch confined in a channel between two longitudinal floating booms in the wave tank. Tows were made at speeds from 0 to 1.7 knots, with included boom angles of 60° and 90°. Visual observations and photographic records were made of these tests. Tows were made both with and without waves. Under these conditions, no significant general boom failure was observed. However, in areas of concentrated vorticity (i.e., the trailing edge of the boom at the gap) sorbent material was observed to be drawn below the surface to depths as great as three feet. Ease of failure is related to saturation of the foam, dry foam floating higher and washing down with less ease than that which has become water saturated. With dry foam, speeds to 3 ft/sec were obtained with an included angle of 90° with no observed failure, in the absence of waves. Waves one foot in height and 12 feet in length produced no failure with wetted foam to a velocity of 1.5 ft/sec. With waves of greater steepness, failure was observed to occur due to splashover or the lifting of the boom's lower edge above the wave troughs in the confused seas created within the 90° convergence area, as shown in Figure 59. Failure due to the lifting of sections of the boom

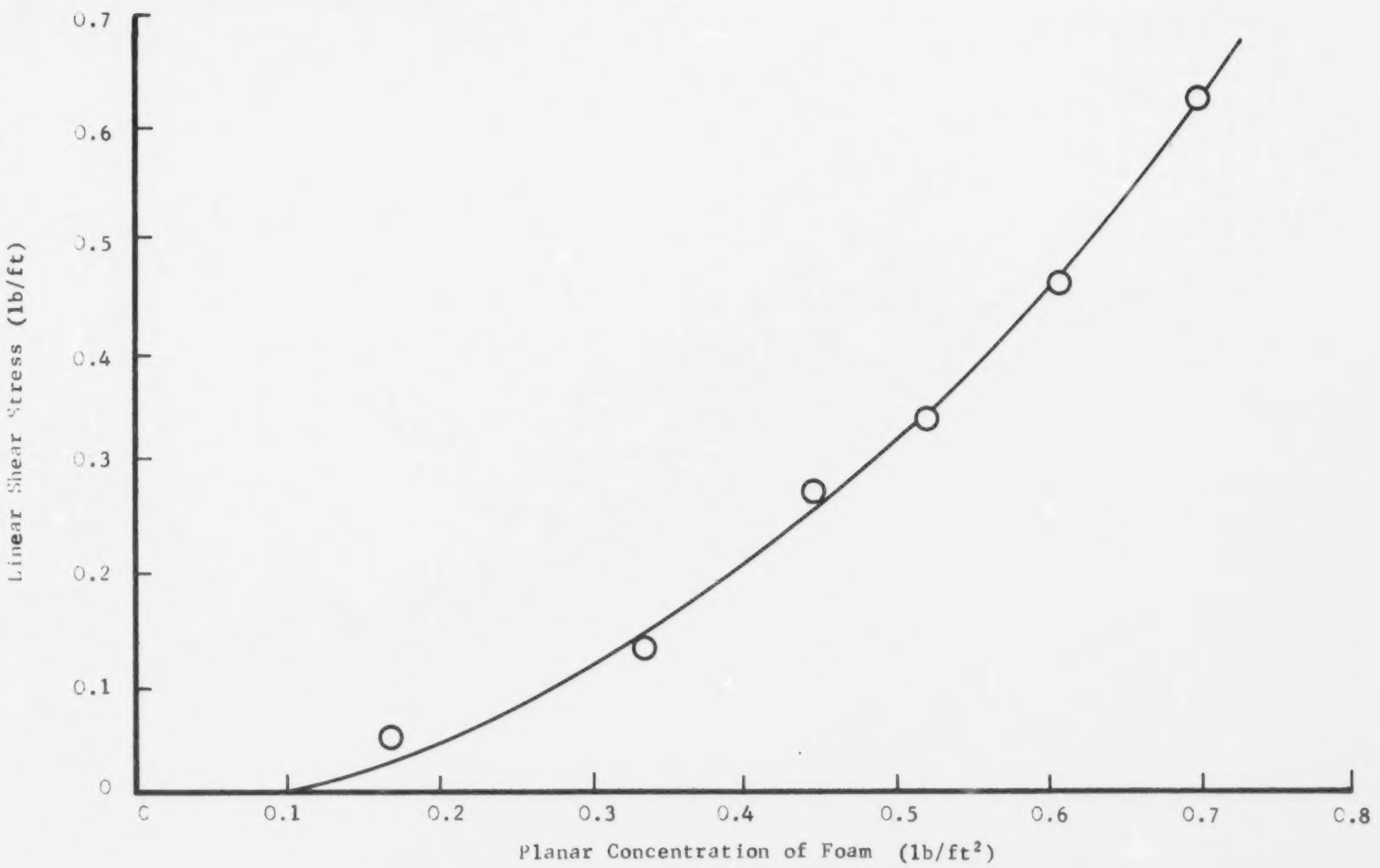


FIGURE 57 - VARIATION IN LINEAR SHEAR STRENGTH OF A SHEET OF MULCHED FOAM ON WATER AS A FUNCTION OF AREA CONCENTRATION

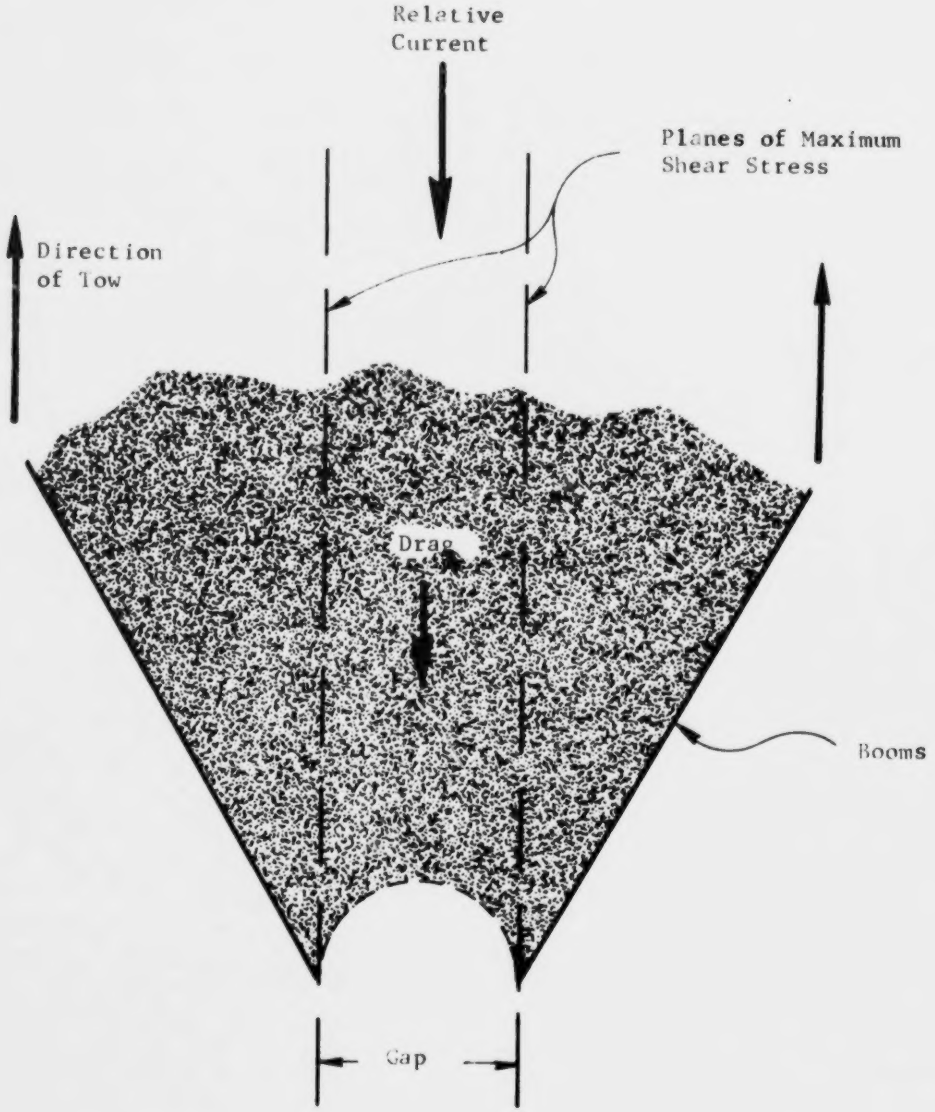

Relative Current
Planes of Maximum Shear Stress
Direction of Tow
Drag
Booms
Gap

FIGURE 58 - BRIDGING OF CONVERGING BOOMS BY FOAM MULCH SORBENT

TABLE 18

PROCEDURE FOR CONFINED FOAM BOOM TOWING TEST

Equipment

1. Laboratory wave tank, 6 x 50 x 120 feet.
2. Fabricated wing structure and boats.
3. One boat for general use.
4. Winch arrangement with forward and reverse.
5. Polypropylene rope.
6. Boom arrangement. Booms converging at desired included angle. Booms are 3-ft x 15-ft.
7. Half-inch mesh chicken wire.
8. Small crab nets to recover foam.
9. Mulched foam.

Procedure

1. Using the winch, position the wing close to the beach.
2. Put a known amount of foam within the confined area between the booms.
3. Start the winch and set on required speed.
4. Immediately after the wing starts moving, the screen across the boom gap is lifted.
5. After the run the wing is pulled back and repositioned close to the beach.

Environmental Conditions

Outdoors, 72°F, light wind.

Ref. SPLC R&D Laboratory Notebook No. LR324.

TABLE 19

PROCEDURE FOR LOOSE FOAM TEST

Equipment

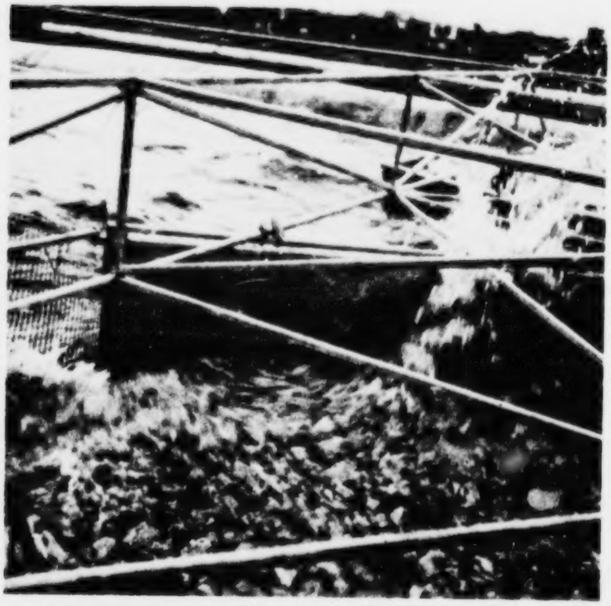
1. Same as in confined foam towing test described in Table 18, excluding chicken wire.
2. Two sections of slickbar boom.

Procedure

1. Same as confined foam towing tests, described in Table 18.
2. Foam is dumped ahead of the fabricated booms between the two slickbars.
3. Wing is towed toward the foam.

Environmental Conditions

Outdoors, 72°F, light wind.



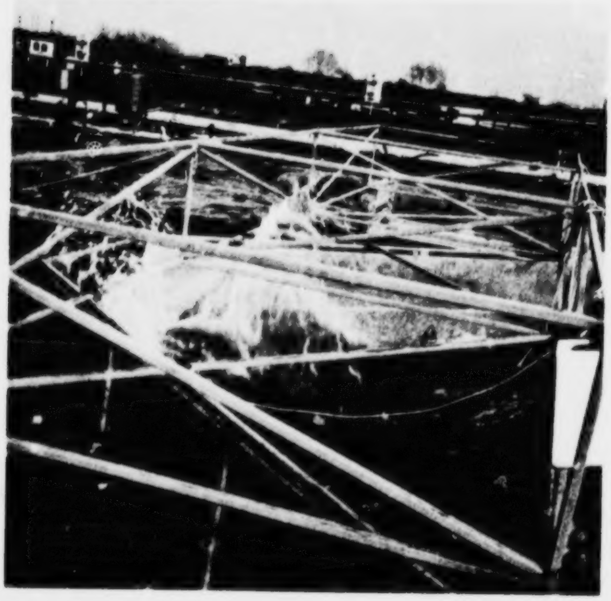
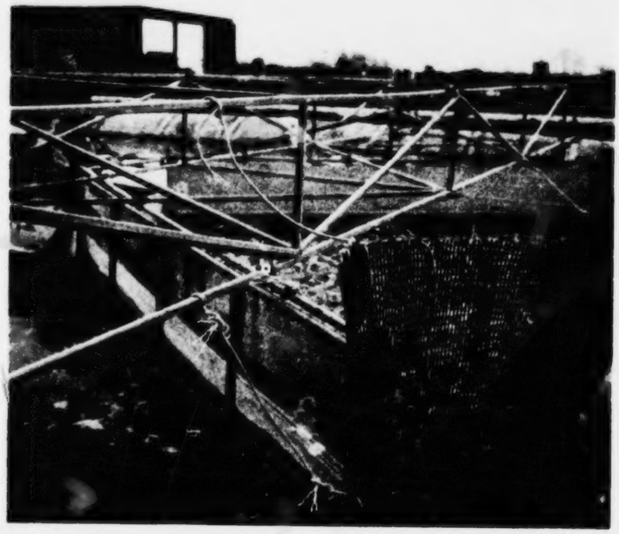


Figure 59 - FAILURE OF BOOMS BY SPLASHOVER AT 1.5 FT/SEC IN PRESENCE OF WAVES

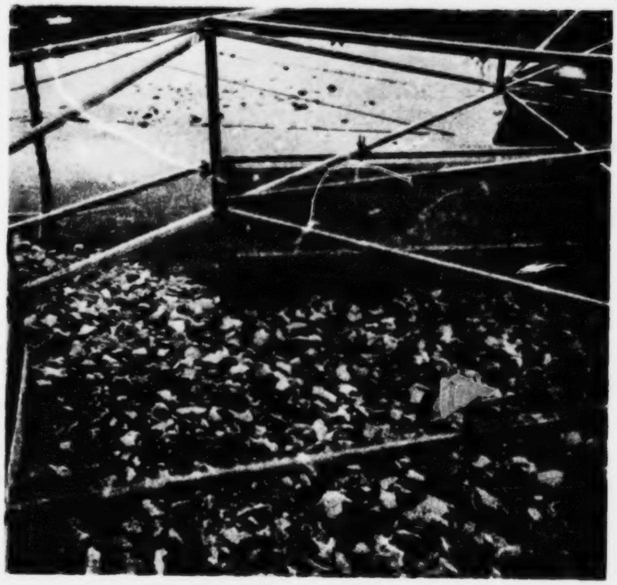
above the water may be mitigated in full scale systems by using articulated strings of boom sections with low longitudinal tension to allow the booms to conform effectively with the contours of the water surface or by using booms of greater draft.

Additional tests were run in which closely controlled concentrations of foam mulch were confined within the included area of the converging booms prior to the initiation of towing and any tendency of the foam to bridge the three-foot boom gap upon getting underway was noted. This test arrangement is shown in Figure 60. The results of 11 such runs are shown in Figure 61. From these data it is expected that bridging will present no substantial obstacle to the performance of a full-scale recovery system. During these experiments failure by foam washing beneath the booms in the absence of bridging was noted only at the highest tow speed, with the boom draft reduced to 13 inches, and only with foam which had been exposed to water over long periods of time so as to render it near neutrally buoyant.

These tests indicate that massive failure should not occur with a properly designed system of booms at the convergence angles and towing velocities anticipated for the full-scale system.



a) Stationary



b) Underway

Figure 60 - BRIDGING TEST ARRANGEMENT

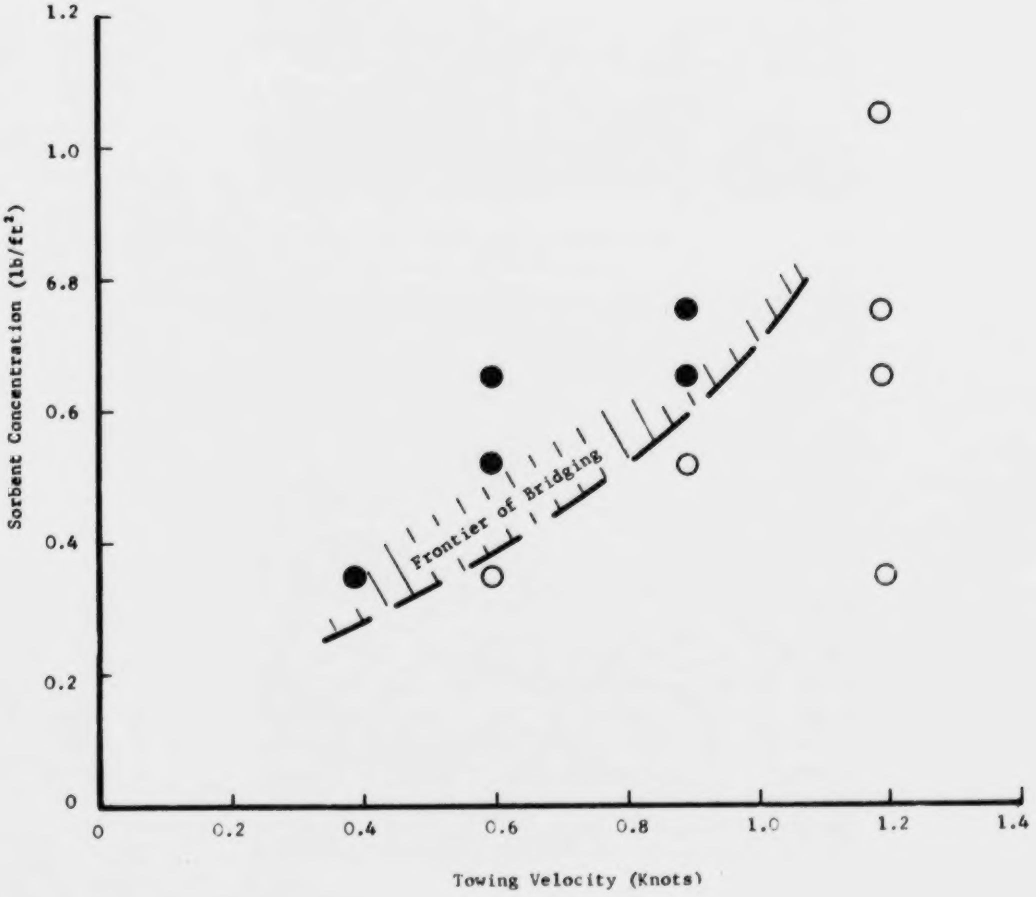


FIGURE 61 - OCCURRENCE OF BRIDGING OF CONVERGING 12-FOOT BOOMS WITH GAP OF 3 FEET AND INCLUDED ANGLE OF 90°. DARKENED SYMBOLS INDICATE OCCURRENCE OF BLOCKING

SECTION X

HARVESTING OF SORBENT

Introduction

In a small system, sorbent can be recovered with nets or mesh drag line buckets. In some cases, recovery by skimming is possible using diaphragm or open impeller pumps. For a high volume continuous system, mechanical belt harvesters appear to be well suited. To avoid the high water recovery expected in skimming, and to take advantage of the fact that the first material which drains from the foam (initial gravity draining) is essentially water, an open mesh belt harvester was investigated in this study.

Open mesh belts are structurally sound, and open mesh belt conveyors have been employed in similar situations in the past. Kelp harvesters used off the California coast and aquatic weed harvesters more recently developed for cleaning lakes use this concept. A tentative selection of belt type was made based on strength, relative amount of open space presented to water flow, and the characteristics of the mulched foam. The minimum foam particle size that would normally be introduced into the system would be retained by a one inch by one inch square mesh. Since the wet foam particles tend to mat and to interlock when in contact with each other, pieces which are somewhat smaller than a one-inch cube would probably not be lost when wet.

The harvesting system studied utilized a flat wire belting (manufactured by Cambridge Wire Cloth Company) with a 1/2-inch x 1-inch mesh. This belt is 3/8-inch thick and is available in a variety of weights and materials. A series of experiments was conducted to investigate the behavior of mulched foam on an inclined conveyor, in air, and in the presence of a water current.

Retention of Foam on an Inclined Stationary Conveyor

Mulched foam was screened and two size ranges were used for this experiment: that retained on a 2-inch square mesh and that which passed through the 2-inch but was retained on a 1-inch square mesh. For each test, the foam was distributed on a horizontal section of 1/2-inch x 1-inch flat wire belt conveyor, either in a single layer or in multiple layers (to a total depth of three inch to six inch). The foam was applied dry, water-saturated, and wrung "dry" by hand.

The conveyor was then inclined while gently shaken. When a significant amount of tumbling or movement of the sorbent was observed, the angle of inclination was recorded.

The results shown in Table 20 suggest that this limiting angle is influenced less by particle size or condition (wet or dry) than by the thickness of the foam layer. This may be explained by the irregular, angular shape of the mulched foam which permits interlocking of particles, making the multi-layer condition more stable than the single thickness in contact with the mesh belt.

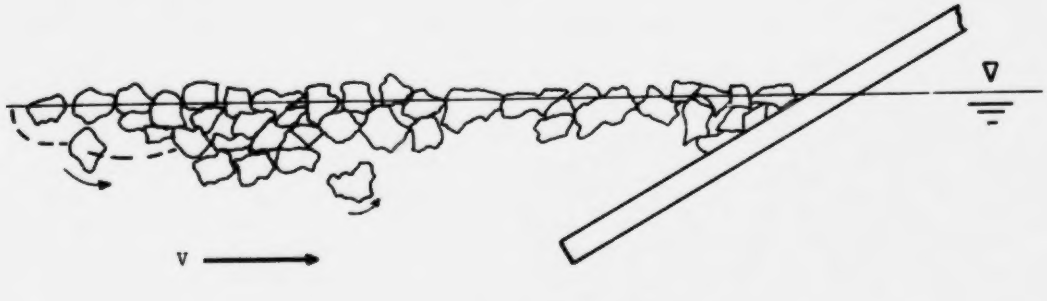
TABLE 20

RETENTION OF FOAM ON AN INCLINED
STATIC BELT CONVEYOR

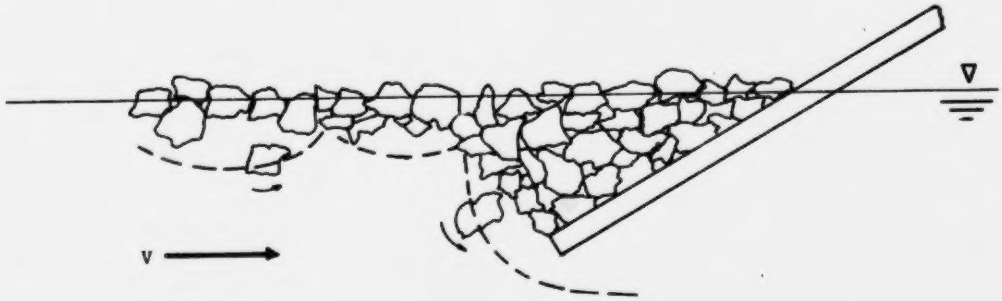
Particle Size Range	Single Layer			Multi-Layer		
	Dry	Saturated	Wrung	Dry	Saturated	Wrung
2-inch mesh	32-36°	37°	35°	40°	39°	39°
1-inch mesh	31°	35°	33°	37°	38°	38°

Foam Collection by Static Inclined Belt in Current

The static belt section was next installed in the current tank to study the behavior of foam approaching in a current and the mode of failure when foam is moved under the belt. The behavior of the foam was observed with the belt at 30° and 40° inclination, and with current speeds from 0.7 ft/sec to 2.0 ft/sec, for the two size ranges of particles described above. Foam reaching the conveyor mesh quickly formed a barrier to the passage of water, oil, or foam. For foam evenly distributed on the water, the initial stages resembled the behavior of an oil film at a boom. Particles at or near the upstream edge of the foam layer were carried under by the action of current and waves. In this early stage, these particles tended to return quickly to contact the under surface of the floating foam layer but would continue to roll until becoming lodged in an opening. A thickening of the layer, not unlike the oil film headwave, was sometimes observed until enough foam had rolled to the conveyor (Figure 62(a)). After a short time, a solid wedge of foam developed at the conveyor (Figure 62(b)) and particles tended to roll under the relatively smooth face of the wedge and past the harvester in a manner similar to that described on page 91. The upstream face of the wedge was approximately 45 degrees from horizontal, regardless of harvester angle. The wedge sometimes became unstable if an unusually large foam particle was exposed on the upstream face. If such a particle was carried away by the current, much or all of the wedge might roll under as a unit before stability could be re-established by filling this void. Substitution of a very fine conveyor mesh had little effect on the behavior of the foam in these tests. Use of the smaller foam particles resulted in more rapid formation of a stable wedge and ultimately a more stable, denser, wedge which presented a smoother upstream face to approaching foam.



(a) Initial Stage of Wedge Development



(b) Fully Developed Wedge with Failure by Particle Rolling

FIGURE 62 - FOAM PARTICLES AGAINST STATIC BELT IN CURRENT

The above observations indicate that failure of foam under a harvester can occur if it stops or slows for even a short period of time. The time until failure would depend, to some extent, on the depth of the conveyor tip.

Operating Prototype Harvester

A small prototype harvester was designed and fabricated for testing in the current and wave tanks. This unit consisted of a 30-inch width of 1/2-inch x 1-inch x 3/8-inch thick flat wire belt in a steel channel frame. The conveyor was driven by an hydraulic motor, and the angle of inclination was adjustable from 0° to 45°. The total weight of the harvester and base was 575 lb, and the effective length (overall) was approximately 10 feet. The prototype harvester is shown in Figure 5.

The harvester was suspended in the current tank so that the lower end was opposite the observation window. A steel mesh basket, 30 inches wide and 7 feet long was suspended over a channel formed by parallel booms. The required amount of foam was placed inside the basket and it was lowered into the stream. The foam was then released through a gate in the downstream end. A screen installed behind the harvester caught any foam lost under the booms or the harvester. Velocities were determined by timing the transit of a portion of the foam over a measured distance in view of the observation window.

Water and air were entrained on the underside of the conveyor and carried to the lower end as the belt speed was increased. When the belt speed became high enough, an upwelling, or bubble barrier, was created at the approach to the belt, often preventing foam from contacting the harvester. This effect is shown in Figure 63. In general, when the ratio of belt velocity V_B to current velocity V_S exceeded about 2.5, a backwash (or counter current) was noticeable on the surface. At a ratio V_B/V_S of 4.0, a counter current of two ft/sec was measured and was observed to persist for ten feet upstream in the narrow channel.

A simple shroud was installed around the lower shaft to divert this current parallel to the rising side of the belt. This shroud was not used in any foam recovery tests. Such a device should be investigated in the design of a harvester to facilitate operation at low current velocities and high belt speeds.

A series of tests was run with the harvester at 30° and at 40° to horizontal. In each series, the belt speed and the approach velocity were varied. The average foam concentration varied from 0.5 to 0.7 lb/ft^2. Recovery rate was determined by the time elapsed from first contact of foam with the belt until the last of the mass was removed. This rate was then expressed as the weight of dry foam recovered per hour. The results are summarized in Table 21. Little or no tendency for the foam to roll or tumble was noted at the 30 degree inclination. At 40 degrees, tumbling significantly affected the recovery rates. To avoid loss of foam by tumbling, four-inch high flights of expanded metal

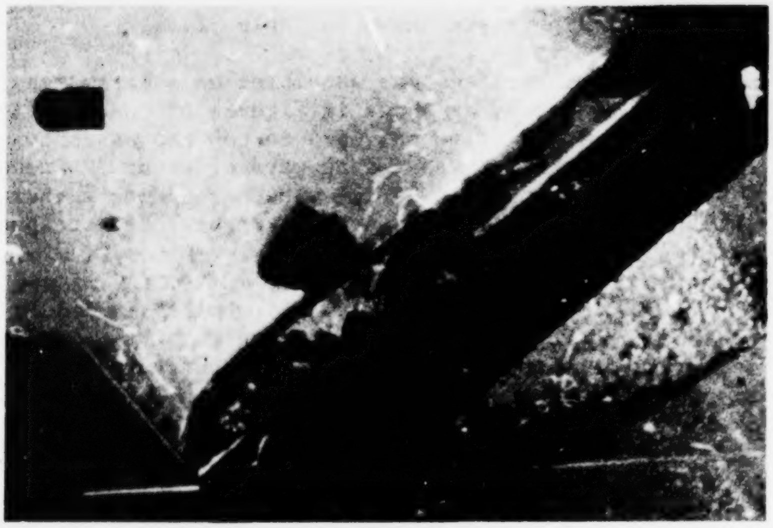


Figure 63 - UPWELLING OF ENTRAINED AIR AND WATER

TABLE 21

SUMMARY OF CURRENT TANK
TEST RESULTS - RANKED

Harvester Angle	Date	Flat Wire Belt Harvester-No Flights					Notes
		Run	V_B (ft/sec)	V_S (ft/sec)	V_B/V_S	Calculated Recovery lb/hr (dry wt)	
30°	11/3	9	2.0	0.8	2.7	1600	
	11/2	1	2.0	2.0	1.0	1480	
	11/2	5	0.8	0.5	1.5	1400	
	11/2	2	2.0	2.0	1.0	1370	1
	11/2	4	0.8	2.0	0.4	1300	
	11/2	6	0.8	0.8	1.0	1300	1
	11/2	7	2.0	0.5	4.0	1300	1
	11/2	8	2.0	0.8	2.7	1300	1
	11/3	1	3.0	0.5	6.0	1300	
	11/3	10	1.0	0.5	2.0	1190	
40°	11/4	18	2.5	2.0	1.3	1420	2
	11/4	4	2.0	1.3	1.5	1410	2
	11/4	19	3.0	2.0	1.5	1270	2
	11/4	11	2.0	2.0	1.0	1200	2
	11/4	7	3.0	1.8	1.7	1200	2
	11/4	5	2.0	1.2	1.7	1120	2
	11/4	12	2.5	2.0	1.7	1120	2

Note 1: **Effect of upwelling observed in belt feed.**

Note 2: **Rate reduced on all runs by tumbling of foam on belt.**

were added at four-foot intervals along the belt, as shown in Figure 64. The results obtained with flights are shown in Table 22.

The harvester, with flights installed, was assembled on a catamaran for towing tests in the wave tank, as shown in Figures 65 and 66. A towing winch with variable speed drive was used to tow the assembly into waves of two types. The first was a long wave of about 12 inches height and 14-foot length (steepness: 14:1). The second was a shorter wave of the same height, but a length of seven to eight feet (steepness: 8:1). A preweighed quantity (dry weight) of foam was placed in a container either dry or in a water wet (but drained) condition. This foam was spread immediately ahead of the harvester, and the times observed in a manner similar to the method of the current tank experiments. Concentration of the foam was estimated as it encountered the short booms at the harvester. Concentrations (area density) of from 0.27 lb/ft^2 to as high as 1.2 lb/ft^2 were observed. Runs were made without waves to correlate with current tank results. All runs were made with the harvester at 40 degrees.

The data suggest that the recovery rate for foam in a calm sea is related to the system velocity more than to any other factor. The curve in Figure 67, shown as "Current Only" represents data from the current tank tests. In most instances, waves improve the recovery by ensuring satisfactory feed to the harvester. With the necessarily small quantities of foam used in these tests, the steep waves were less effective than the longer waves, largely due to a cross chop which developed within the short 45 degree boom array (cross chop would not be so severe in a longer array at lesser angles). This situation is shown in Figure 68. Longer waves, more nearly resembling in shape those expected in operation, had a significant effect on recovery rate.

Recovery rate in waves is affected by foam concentration. This effect is exaggerated in our experiments, in which the foam batch size was limited (the feed rate declines at the tail end of a small batch since no additional foam is present to provide a driving force).

The manner in which wet foam is retained on the harvester with flights is shown in Figure 69. The wedge results in part from the tumbling of foam on the moving belt; a reduction in flight spacing would increase the capacity of the harvester. The figure shows a mass of foam of an estimated equivalent dry weight of 4.8 lb which was picked up at a belt velocity of 2.0 ft/sec and system velocity of 3.0 ft/sec. Assuming equal recovery by each flight, the recovery rate might be:

$$\frac{4.8\ \text{lb}}{\text{Flight}} \times \frac{2.0\ \text{ft}}{\text{Sec}} \times \frac{3600\ \text{Sec}}{\text{Hr}} \times \frac{\text{Flight}}{4.0\ \text{ft}} = 8700\ \text{lb/hr}$$

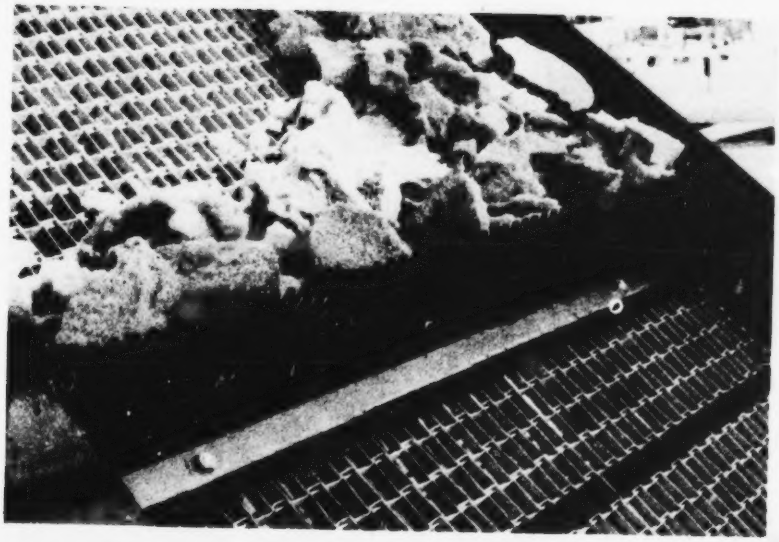


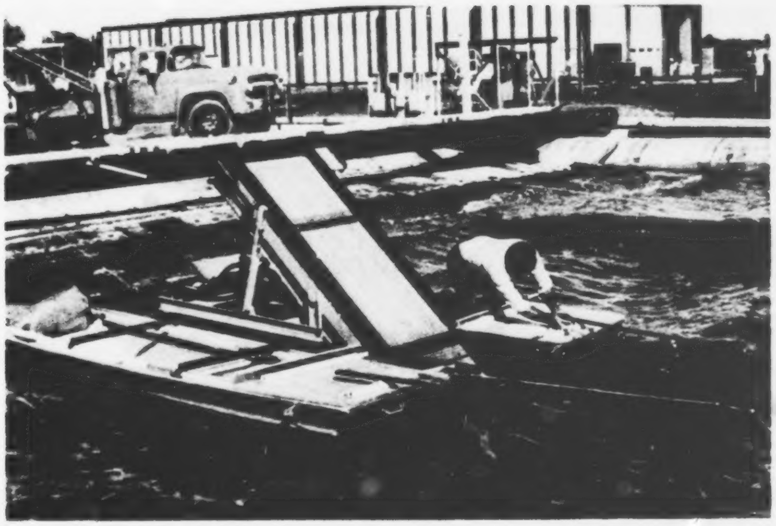
Figure 64 - 1/2" x 1" FLAT BELT HARVESTER WITH EXPANDED METAL FLIGHTS

TABLE 22

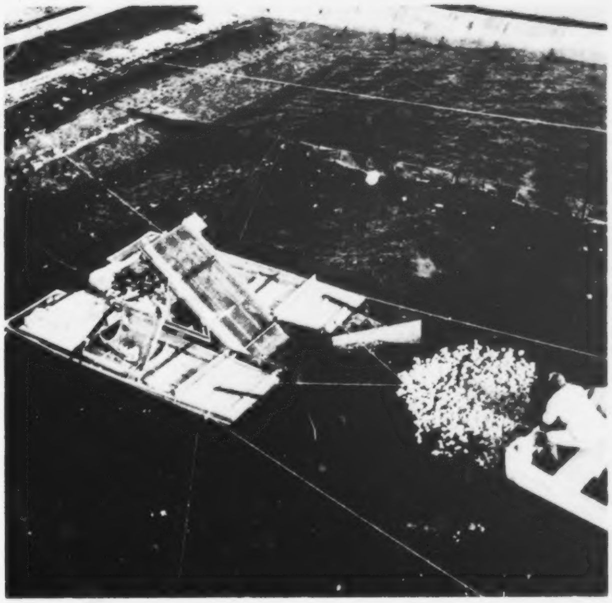
SUMMARY OF CURRENT TANK TEST RESULTS - RANKED

Harvester Angle	Date	Flat Wire Belt Harvester - 4" Flights					Notes
		Run	V_B (ft/sec)	V_S (ft/sec)	V_B/V_S	Calculated Recovery (lb Dry Wt./hour)	
30°	11/12	4	4.0	1.5	2.7	9400	
	11/11	6	3.0	1.0	3.0	6200	
	11/11	7	5.0	0.9	5.6	5200	
	11/11	4	3.0	1.0	3.0	4600	
	11/11	8	2.0	1.0	2.0	4700	
	11/11	5	1.0	0.5	2.0	4300	
	11/12	8	3.0	0.8	3.8	4100	
	11/11	3	4.0	1.0	4.0	3600	
	11/11	13	5.0	1.0	5.0	2000	1
	11/11	12	5.0	1.0	5.0	1600	1
40°	11/9	4	4.0	1.3	3.2	5200	
	11/9	6	4.0	1.3	3.2	5200	
	11/12	3	3.0	1.5	2.0	5200	
	11/9	5	4.0	1.3	3.2	4700	
	11/9	3	3.0	1.3	2.4	4500	
	11/9	2	2.0	1.3	1.6	3900	
	11/10	3	3.0	0.7	0.4	1600	1

Note 1: Upwelling effect observed.

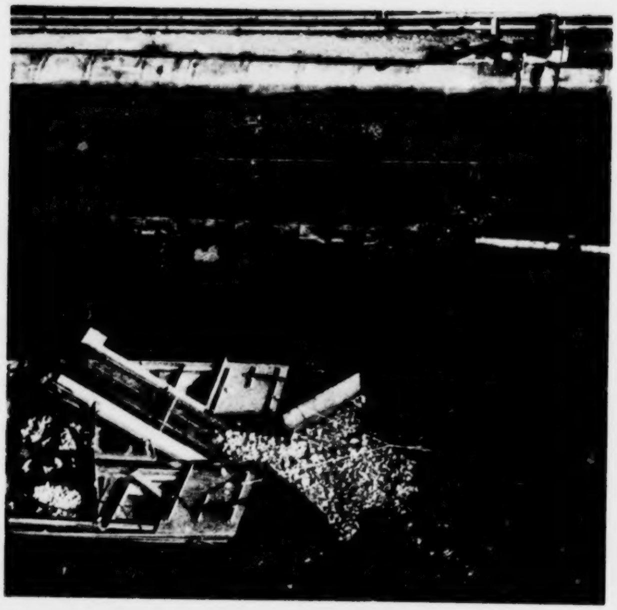


(a)

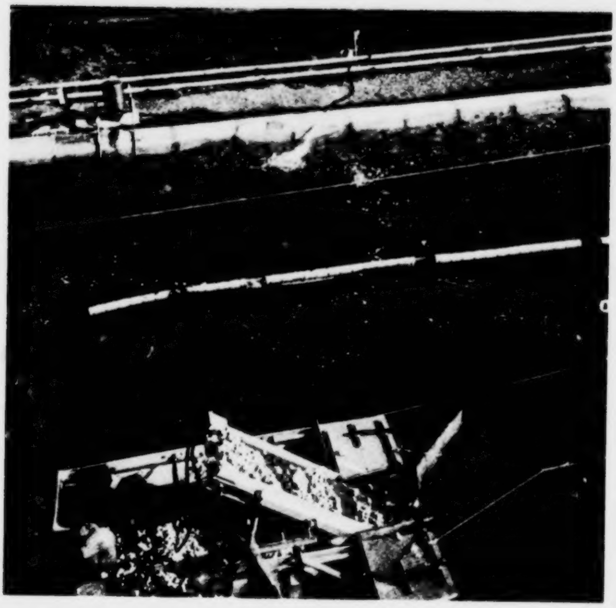


(b)

Figure 65 - HARVESTER IN WAVE TANK



(a)



(b)

Figure 66 - TOWING INTO 14-FOOT LONG WAVES AT 2.0 FT/SEC

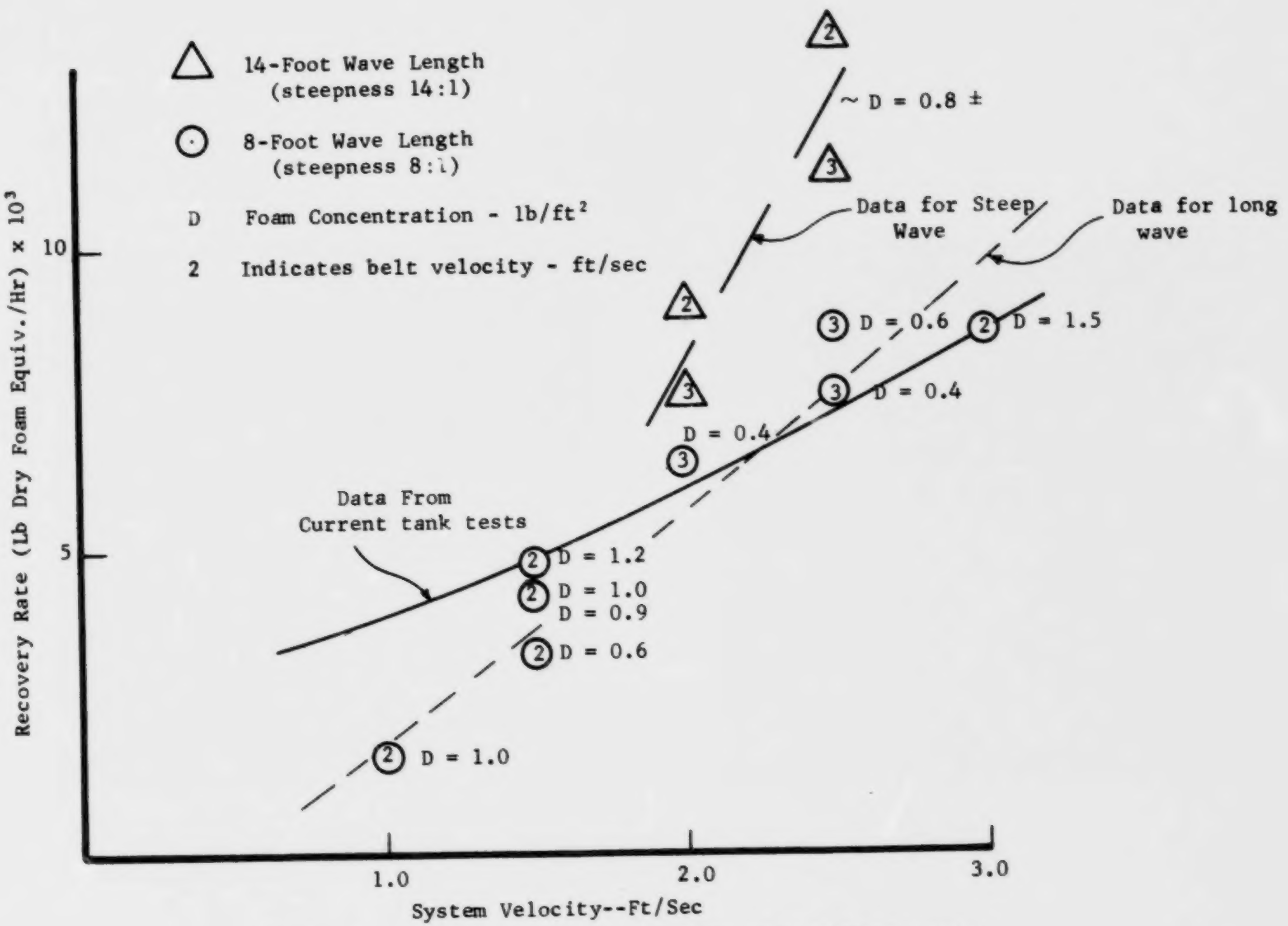


FIGURE 67 - EFFECT OF WAVE FORM AND FOAM CONCENTRATION

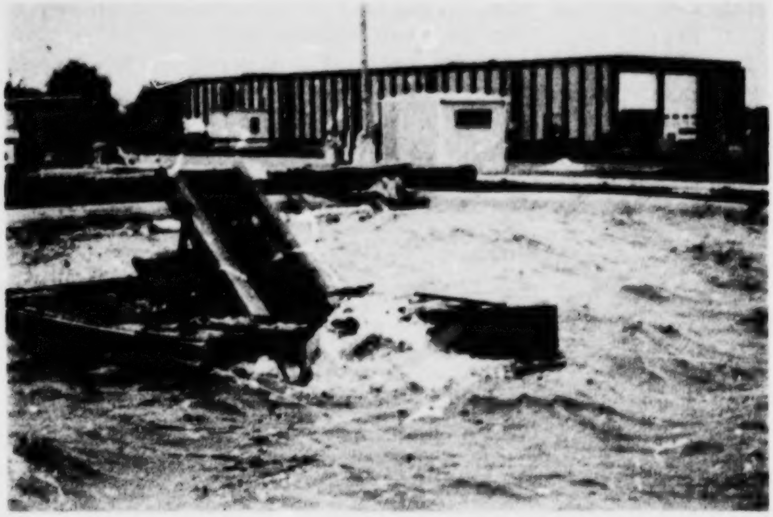


FIGURE 68 - TOWING INTO 8-FOOT LONG WAVES AT 2.5 FT/SEC

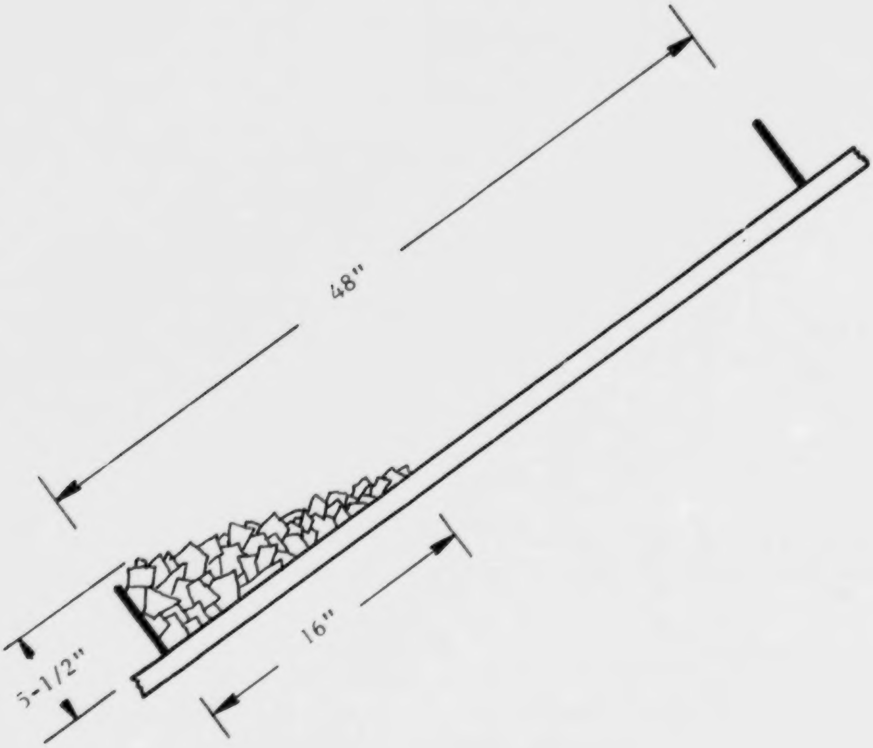


FIGURE 69 - TYPICAL LOADING OF 4-INCH EXPANDED METAL FLIGHT AT HARVESTER ANGLE OF 40°, BELT SPEED = 2 FT/SEC, SYSTEM VELOCITY = 3 FT/SEC

which agrees with the experimental results for steep waves or for no waves as shown in Figure 67. The average volume recovery calculated for this 2.5 ft belt width is 1380 ft^3/hr (actual volume), giving an apparent or packing density (dry weight equivalent) of:

$$\text{packing density} = \frac{8700 \text{ lb}}{\text{Hr}} \times \frac{\text{Hr}}{1380 \text{ ft}^3} = 6.2 \text{ lb/ft}^3$$

The actual dry density of this foam batch was approximately 2.0 lb/ft^3.

Foam Packing Density During Handling

To assist in the design of all conveying components, a series of design curves was prepared based upon simple bench scale density experiments in which a wire mesh basket, 24 inches square, fabricated from 1/2-inch square mesh was filled with foam, without compaction, and the occupied volume was estimated. The initial measurement was with mulched dry foam. The same foam was water soaked for three minutes then returned to the basket. Foam in this "wet" condition would represent saturated foam after some 30 seconds draining. Again, the same foam was soaked, wrung by the experimental wringer, and returned to the basket. The results are shown in Table 23.

TABLE 23

APPARENT OR "PACKING DENSITY" OF FOAM
WITHOUT COMPACTION

	2.0 lb Sample		4.8 lb Sample		Average
Foam	Volume (ft^3)	Apparent Density (lb/ft^3)	Volume (ft^3)	Apparent Density (lb/ft^3)	Apparent Density (lb/ft^3)
Dry Foam	1.7	1.2	3.3	1.4	1.3
Wet	1.0	2.0	2.3	2.0	2.0
Wrung	1.3	1.5	2.7	1.8	1.6

As a design aid, the unit recovery rate for foam might be defined as the equivalent dry weight of foam recovered per hour per unit width of system - Q'_H:

$$Q'_H = d_{s_{avg}})(V_B)(3600)(d)$$

Where

Q'_H = lb/hr - ft width

t_{avg} = thickness of foam layer - ft

V_B = belt velocity - ft/sec

d = apparent foam density - lb/ft^3

The apparent or packing density of typical batches of mulched foam has been determined for four conditions:

a. Dry
b. Water-saturated, driven by current
c. Water-saturated, drained
d. Water-saturated, wrung

These values are of interest in estimating mass flow and power requirements for all system components. An estimate of the average density during transit from water surface to deck may be of use in harvester design. The average (condition e) of (b) and (c) was used in Section XIV.

SECTION XI

WRINGING

Introduction

The ability to efficiently recycle the polyurethane foam sorbent depends upon the ability to remove oil quickly from the foam during the relatively short cycle time. A simple roller wringer appears to best satisfy the need for a continuous, simple, reliable system. A wringer can be readily integrated with a conveyor system. Rollers can be easily fabricated from large diameter pipe and may be filled with water or other fluids to increase wringing pressures.

Wringing Experiments with Oil and Foam Cubes

A wringing apparatus was constructed for study as pictured in Figure 70 and shown schematically in Figure 71. The unique feature of this design is the wire mesh conveyor belt which supports the foam as it passes through the wringer. The conveyor mesh (purchased from Cyclone Fence Sales, U. S. Steel Corporation, Houston, Texas) had openings 1/4-inch x 1/2-inch and was 1/8-inch thick, as shown in Figure 72. Both rollers in our early experiments had diameters of 6-3/4 inches and were 36 inches long. The top roller was free to move vertically so that the foam was wrung under constant pressure. The wringer was operated in later experiments with a 24-inch diameter top roller (Figure 6). Wringing pressure was varied by filling the rollers with water or by hanging weights on the ends of the top roller (Figure 70). When the small diameter wringer roller was used, the conveyor was driven by a hand crank. For the experiments with the large diameter roller the conveyor was driven by a 3-horsepower motor through a variable speed reduction unit.

Initial experiments were performed by wringing oil from 2-inch foam cubes. Details of the procedures are given in Table 24. Decreasing the conveyor speed, increasing the roller weight, and increasing the number of passes through the wringer resulted in more complete oil-sorbent separation. Significantly, the rate of improvement in the wringing performance diminished with increasing wringing pressure, decreasing conveyor speed, and increasing number of passes through the wringer. Thus, the satisfactory performance found at manageable roller weights and conveyor speeds coul not be greatly improved. The experiments showed that there was residual oil which could not be removed even by extensive squeezing. The amount of residual oil increased with increasing oil viscosity.

Effect of Wringer Pressure, Conveyor Speed, and Number of Passes Through the Wringer

Figure 73 shows the oil remaining in the foam as a function of the "pressure" imposed by the wringer. The foam pressure is equal to the roller weight divided by the length of the foam presented to the roller. (For the foam pictured in Figure 71 the length of foam is 12 inches.) For each experiment

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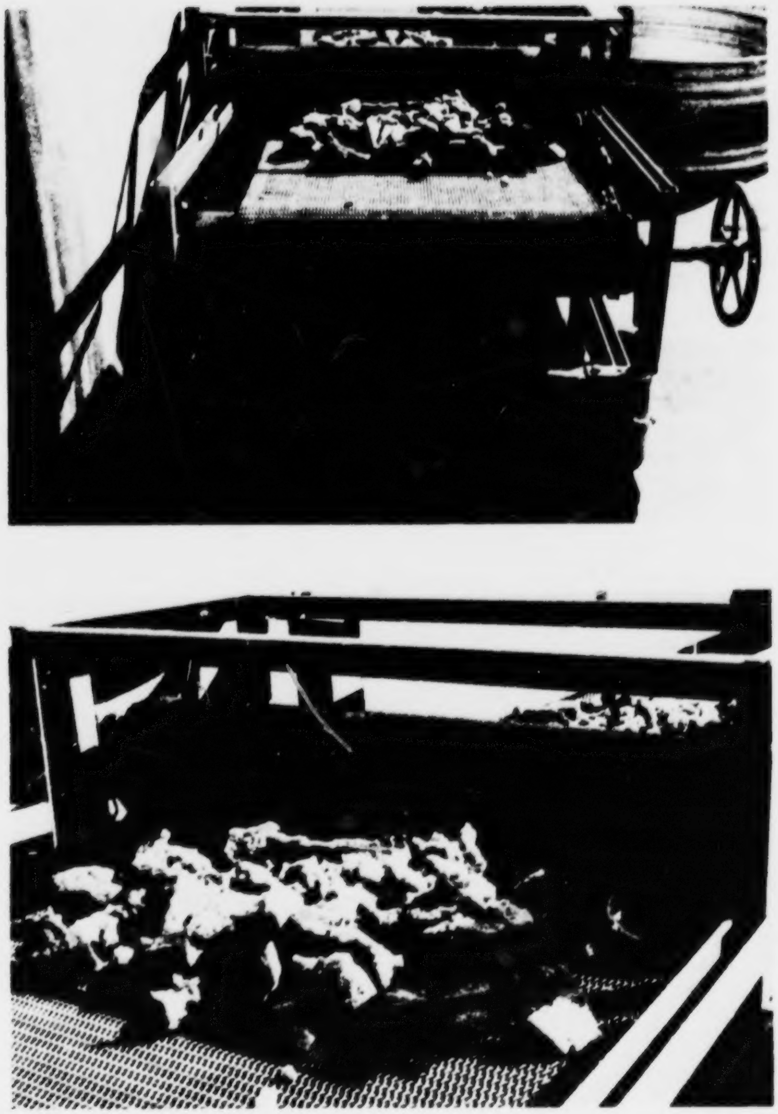


Figure 70 - PHOTOS OF APPARATUS WRINGING MULCHED FOAM IN ARRANGEMENT TYPICAL OF THAT USED IN THE EXPERIMENTS

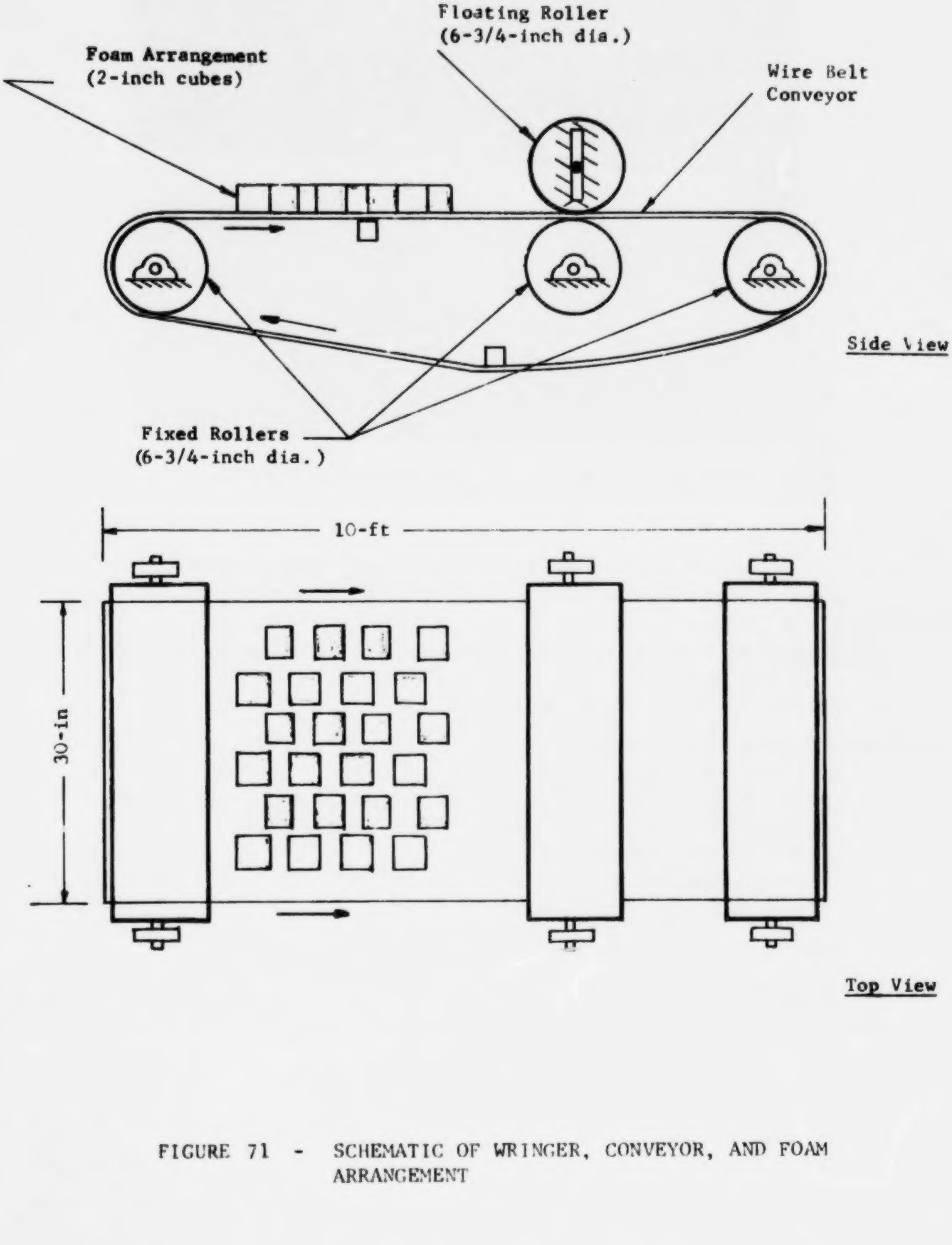

Floating Roller
(6-3/4-inch dia.)
Foam Arrangement
(2-inch cubes)
Wire Belt
Conveyor
Side View
Fixed Rollers
(6-3/4-inch dia.)
10-ft
30-in
Top View

FIGURE 71 - SCHEMATIC OF WRINGER, CONVEYOR, AND FOAM ARRANGEMENT

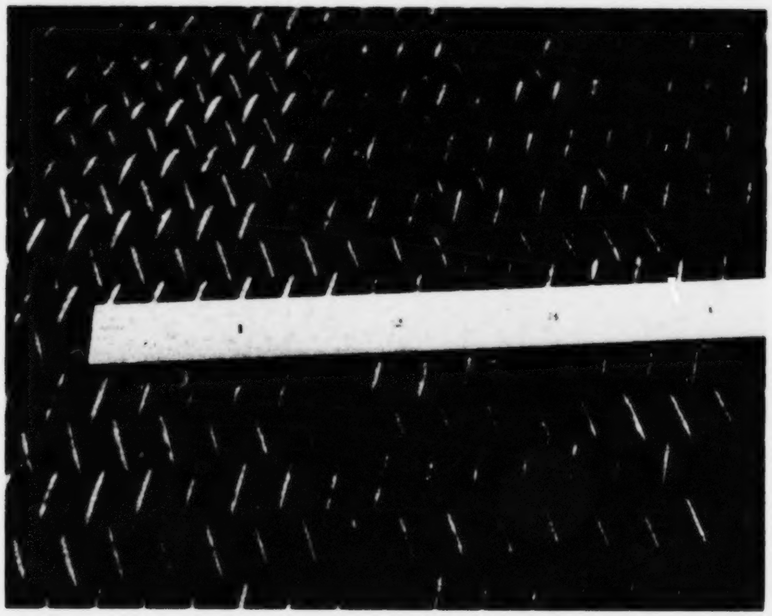


Figure 72 - DETAIL OF WIRE MESH CONVEYOR BELT

TABLE 24

WRINGING EXPERIMENTS USING 2-INCH FOAM CUBES

Equipment:

1. Roller wringer using 6-3/4" diameter roller (see Figures 70 and 71)
2. A triple beam balance
3. Supply of 2-inch foam cubes

Experiment Procedure:

1. Determine dry foam weight.
2. Place foam cubes on an excess of oil until fully saturated.
3. Allow oil to drain until free oil is removed.
4. Weigh oil-saturated foam.
5. Arrange foam cubes on conveyor in pattern shown in Figure 71.
6. Accelerate conveyor to desired speed.
7. Weigh foam cubes after wringing.
8. Repeat steps 5-7 desired number of times.

Environmental Conditions:

Experiments performed outside, temperature 72-82°F

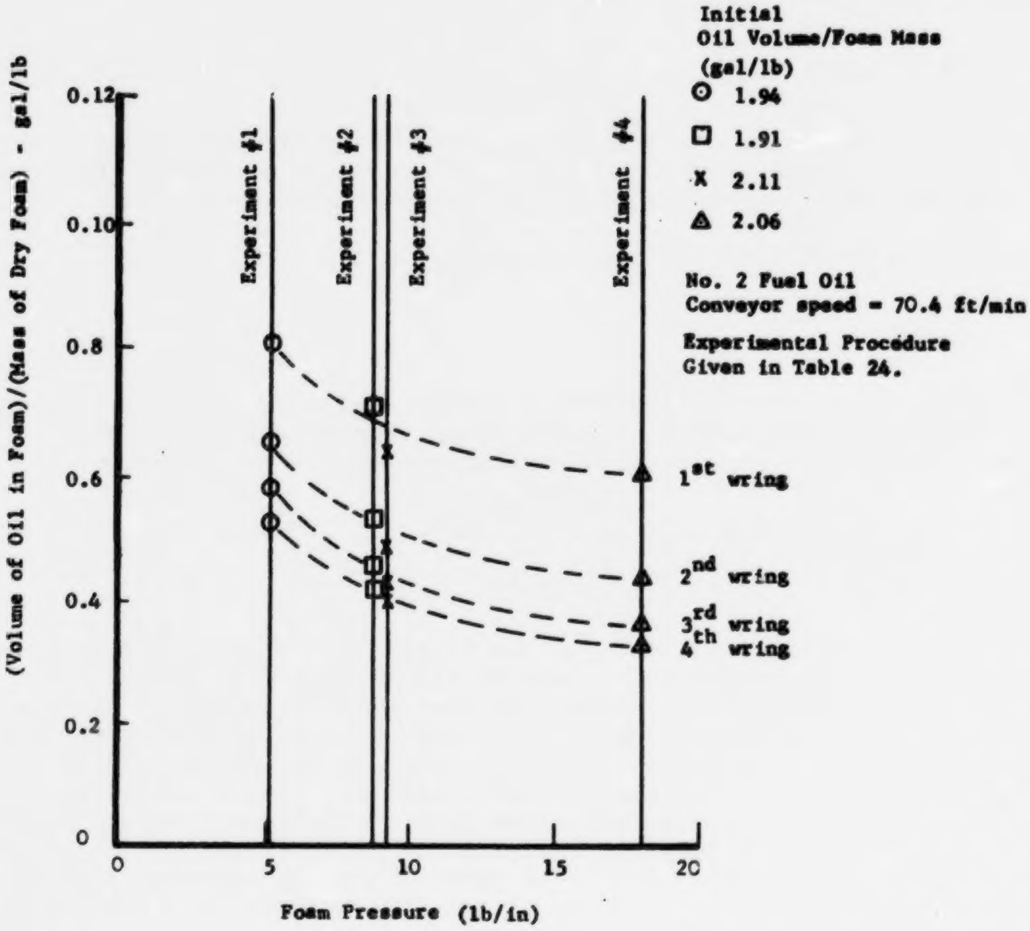


FIGURE 73 - VOLUME OF OIL/FOAM MASS VS IMPOSED FOAM PRESSURE

the foam was wrung four times. It may be seen that the advantage of wringing the foam more than three times is minimal. With increasing foam pressure there appears to be a limiting quantity of oil retained by the foam at each wring.

Figure 74 shows that the oil remaining in the foam increases, though not greatly, with increasing conveyor speed. After four wrings, the amount of oil remaining in the foam at a conveyor speed of 35 ft/min is only 15% less than that remaining at 105 ft/min.

The results of these experiments can be correlated by assuming that the rate of oil removal from the foam is given by

$$\frac{dQ}{dt} = -GP\,(Q - Q_\infty) \qquad (11)$$

where Q is the volume of oil in the foam, Q_∞ is the oil permanently retained or trapped in the foam, P is the weight of the roller divided by the length of the foam under the roller and G is a dimensional constant.

Integrating from the initial oil volume, Q_o, at t = 0,

$$\frac{Q - Q_\infty}{Q_o - Q_\infty} = e^{-GPt} \qquad (12)$$

Assuming that t, the time the foam is exposed to the wringer pressure, can be expressed as the product of a dimensional constant and the number of passes through the wringer, N, divided by the wringer roller RPM, w, we have

$$\frac{Q - Q_\infty}{Q_o - Q_\infty} = e^{\frac{-G'PN}{w}} \qquad (13)$$

Figure 75 presents a correlation of the data using the parameters PN/w and $(Q - Q_\infty)/(Q_o - Q_\infty)$ suggested by Equation 13. The data are for a range of roller weights and conveyor speeds, for four different viscosity oils, and for each of four passes through the wringer. The data show by virtue of the correlation that the percent of oil removed is independent of the viscosity of the oil; but, as shown in Table 25, the increased viscosity affects the value of Q_∞, the oil volume which is not removed by wringing. The data in Figure 75 appear to intercept the y-axis at 0.4, but before wringing the value must be 1.0. This suggests that an appreciable amount of the oil, possibly the oil on the surface of the cubes, is removed by some mechanism not described by Equation 13.

Effect of Recycling and Aging of Sorbent

In Table 26 results are presented from a series of tests performed to study the effect of the number of cycles and the oil-sorbent exposure time on wringing performance. The table shows that wringing performance is not

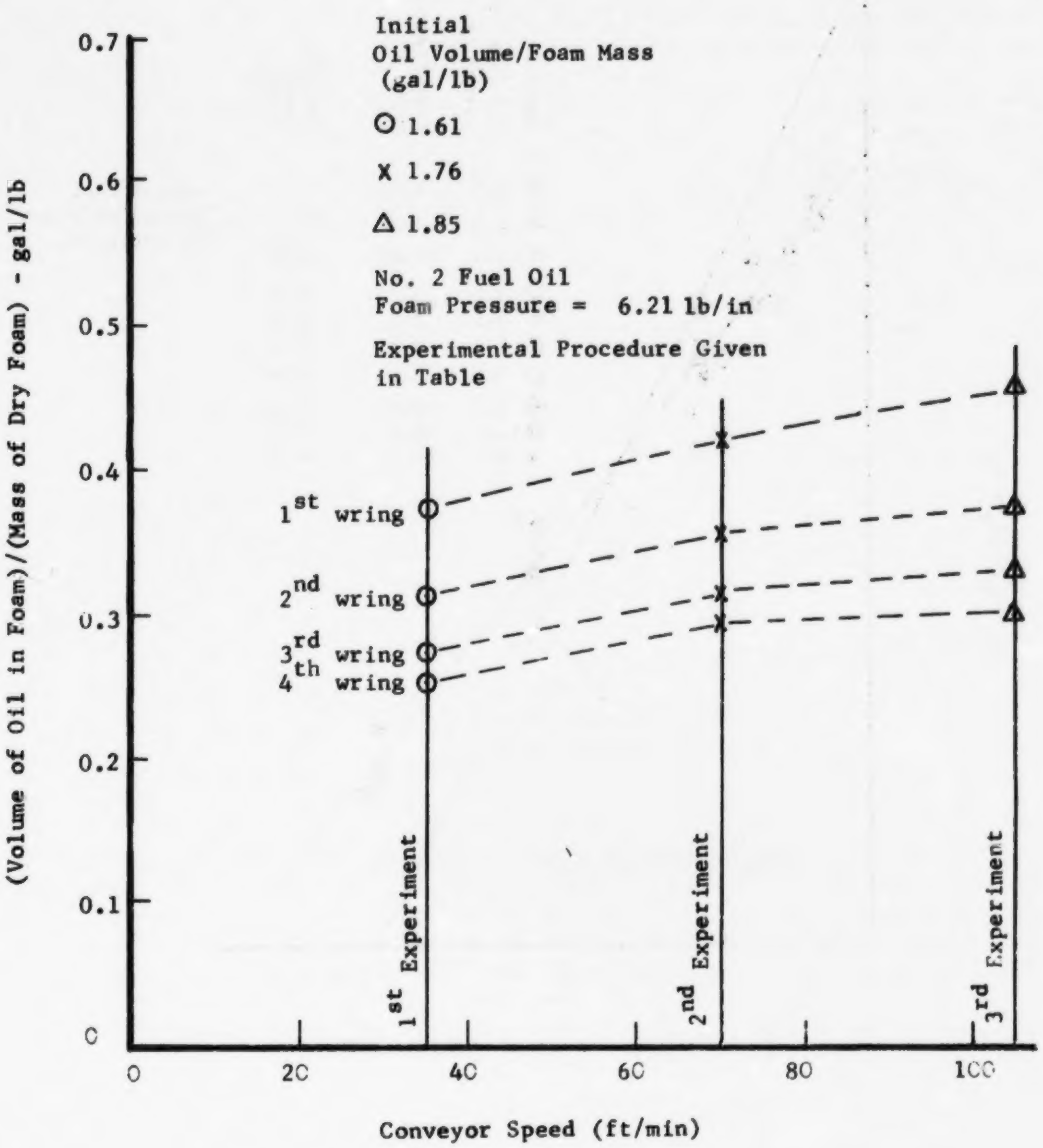


FIGURE 74 - VOLUME OF OIL/FOAM MASS VS CONVEYOR SPEED

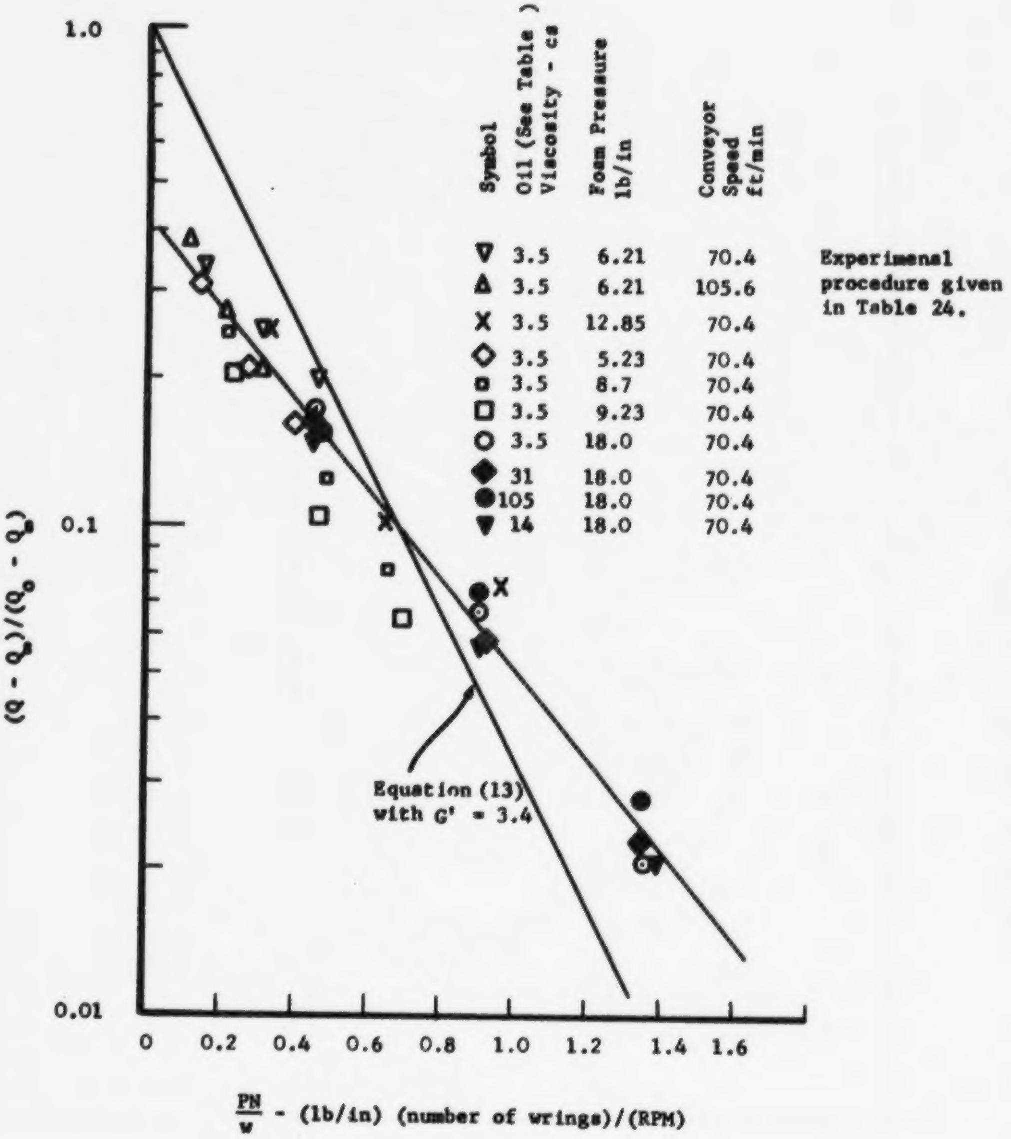


FIGURE 75 - CORRELATION OF WRINGING DATA FROM EXPERIMENTS USING ONLY OIL AND 2-INCH FOAM CUBES

TABLE 25

PERMANENTLY RETAINED OIL IN 2-INCH POLYURETHANE FOAM CUBES

Conditions:

Oil retained by foam after 4 wrings using procedure described in Table 25.

Conveyor Speed = 70.4 ft/min
Foam Pressure = 18 lb/min

Oil	Viscosity at 80°F (cs)	Q_∞ (gal/lb dry foam)
No. 2 Diesel	3.5	0.33
Carnea 15	14.0	0.43
Carnea 21	31.0	0.48
Shallow Yates	105.0	0.63

TABLE 26

EFFECT OF TIME AND WRINGING CYCLES ON WRINGING PERFORMANCE

(All tests performed by recycling foam first used in Run No. 1)
No. 2 Fuel Oil Used for Tests

Run	(Volume of Oil in Foam)/(Mass of Dry Foam)-gal/lb					Final Oil After 4th Wring, % Increase over Run No. 1
	Initial	1st wring	2nd wring	3rd wring	4th wring	
1	1.83	0.50	0.34	0.29	0.27	--
	Above procedure (Run No. 1) repeated five times without weighing and with no time lapse between tests.					
7	1.83	0.58	0.41	0.32	0.29	8.7
	6 hour time lapse					
8	1.67	0.60	0.42	0.34	0.30	14.8
	26 day time lapse					
9*	0.96	0.47	0.33	0.27	0.24	-10.9

* For Run No. 9 the foam was not soaked in oil for as long a time as in the previous runs. This resulted in the lower initial oil content in the cubes.

Foam Pressure = 21.7 lb/in

Conveyor Speed = 70.4 ft/min

Experimental procedure given in Table 24.

greatly affected by recycling nor by storing the foam in contact with oil for a time period of 26 days. The data of Table 27 show that there is little or no effect on wringing performance of aging of dry foam for periods to one month.

TABLE 27

EFFECT OF FOAM AGING ON WRINGING PERFORMANCE

Run	(Volume of Oil in Foam)/(Mass of Dry Foam) - (gal./lb)					Final Oil After 4th Wring % Decrease Over Run No. 1
	Initial	1st wring	2nd wring	3rd wring	4th wring	
1	1.83	0.50	0.46	0.29	0.27	--
	One week time lapse					
2	1.73	0.48	0.34	0.29	0.26	4.3%
	One month time lapse					
3*	1.09	0.46	0.32	0.27	0.24	8.6%

* For Run No. 3 the foam was not soaked in oil for as long a time as for Runs No. 1 and 2. This resulted in the lower initial oil content.

Foam Pressure = 21.7 lb/in.
Conveyor Speed = 70.4 ft/min
No. 2 Fuel Oil used for tests.
Experimental procedure given in Table 24.

Wringing Oil and Water from Mulched Foam

The results of the experiments using both oil and water agree qualitatively with those described above. The experiments were of a practical nature. Mulched foam (see Table 12 for the foam size distribution) was placed on a water-filled 5-foot diameter tank on which oil had been spread. The foam was allowed to sorb oil and water for approximately three minutes, lifted from the tank, allowed to drain, and successively wrung. The foam was recycled in this manner, simulating the recycling process anticipated for the actual collection system. The detailed experimental procedure is given in Table 28.

The first experiments were performed using the small diameter roller, 2.2 lb of dry foam, and 0.65 gal. No. 2 Fuel Oil. The oil was placed on the tank for each cycle resulting in an initial slick thickness of 0.06 in. In Figure 76 the transient behavior of the foam during recycling is presented. The oil, water, and total liquid recovered by the four wrings in each cycle are plotted as a function of the number of the soaking-wringing cycle. In each case the fluid volumes plotted have been divided by the dry weight of the foam. Figure 76 shows that the transient process continues over the first four cycles, during which oil content of the effluent increases from

TABLE 28

WRINGING EXPERIMENTS USING MULCHED FOAM

Equipment:

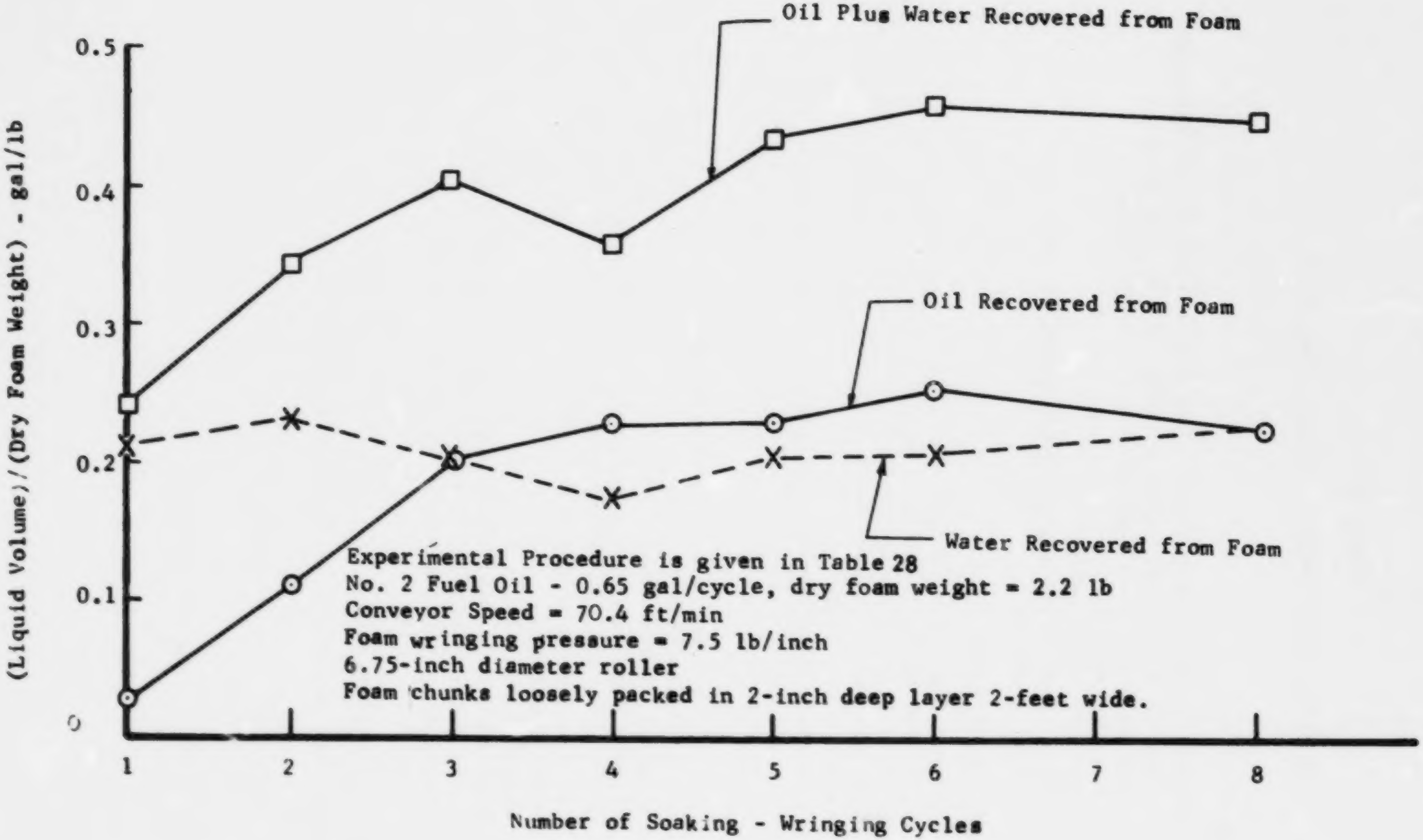
1. Roller wringer using 6-3/4" diameter roller or 24" diameter roller as specified. (See Figures 89, 6, and 92.)
2. A 5-foot diameter 3-foot deep thin walled tank.
3. A hanging scale.
4. Nylon net, 1/4" mesh.
5. Mulched foam (size distribution given in Table 12).
6. 2000 ml graduate.

Experimental Procedure:

1. Determine dry foam weight (typically 2.2 lb).
2. Place two feet of water in 5-foot diameter tank.
3. Place desired quantity of oil on the water surface (typically 0.65 gallons). Note: This amount of oil is not sufficient to saturate the foam.
4. Distribute foam evenly over water surface and allow it to sorb oil for 2-3 minutes until all oil is in foam, by visual inspection. To promote oil contact, move foam slowly over water surface.
5. Lift oil-soaked foam from tank using nylon net. Allow free oil to drain off.
6. Weigh oil soaked foam.
7. Arrange foam on wringer conveyor in a layer of the desired depth. Figures 89 and 92 show typical foam arrangement.
8. Start conveyor at desired speed.
9. Weigh wrung foam.
10. Repeat steps 7-9 as desired.
11. Measure oil and water volumes removed by wringing.
12. Clean water surface on 5-foot diameter tank.
13. Repeat steps 3-12 using the same foam sample for the desired number of cycles.

Environmental Conditions:

Experiments performed outside, temperature 55-75°F.



Experimental Procedure is given in Table 28
No. 2 Fuel Oil - 0.65 gal/cycle, dry foam weight = 2.2 lb
Conveyor Speed = 70.4 ft/min
Foam wringing pressure = 7.5 lb/inch
6.75-inch diameter roller
Foam chunks loosely packed in 2-inch deep layer 2-feet wide.

FIGURE 76 - TRANSIENT BEHAVIOR OF SOAKED FOAM DURING RECYCLING

approximately 10% to greater than 50%. The amount of water removed from the foam is approximately constant, suggesting that water is not accumulating within the foam during this initial period. One encouraging result is that the total liquid recovered increases during the transient period. In Figure 77 the wringing performance during the first, third, sixth, and eighth cycle is presented. The weight of the liquid retained by the foam divided by the dry foam weight is plotted versus the number of times the foam is wrung. It is seen that, except for the first cycle, the weight of the liquid retained after four passes through the wringer is unchanged. In Table 29 the results are presented of an experiment to determine the percent oil removed during successive wrings. The experiment was performed using the foam sample which had been cycled eight times as described above. Table 29 shows that the percent oil removed increases only slightly during successive wrings.

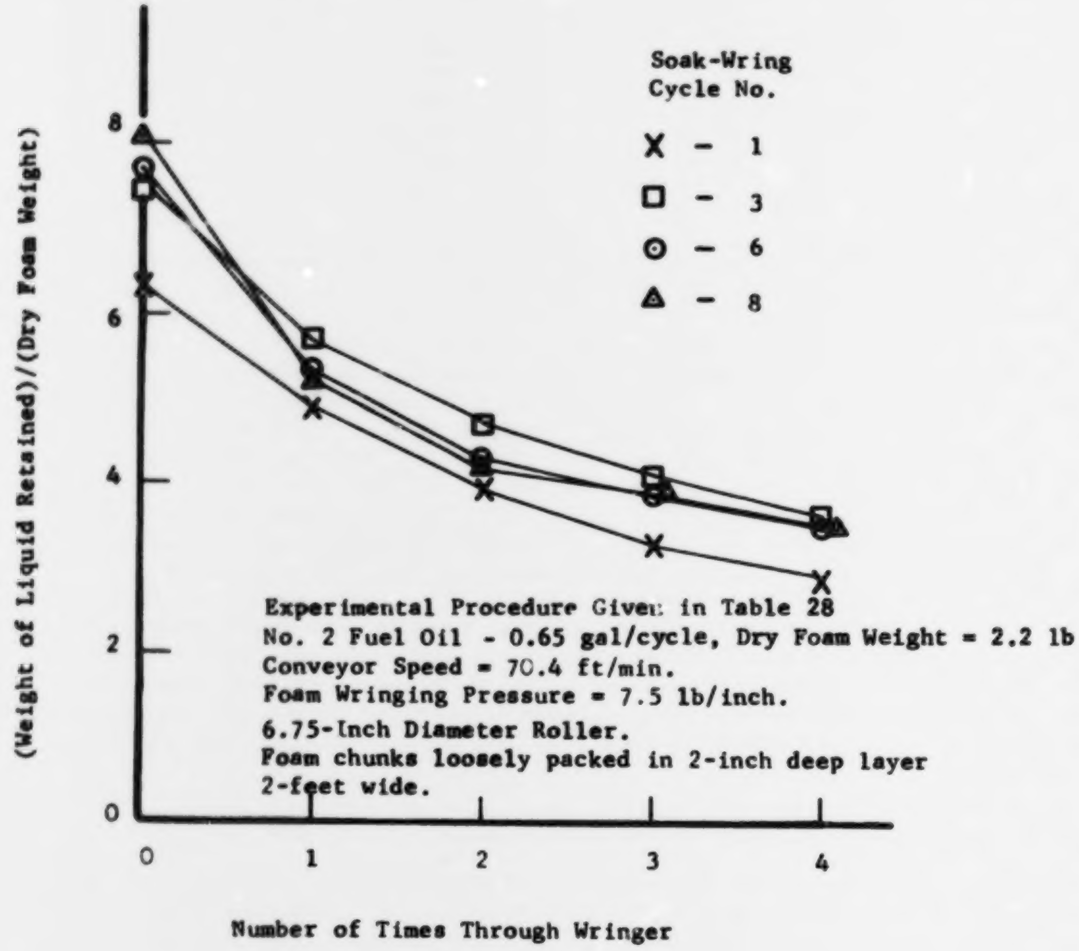


Figure 77 - WRINGING PERFORMANCE FOR DIFFERENT NUMBER OF CYCLES

TABLE 29

PERCENT OIL REMOVED BY SUCCESSIVE WRINGINGS

Conditions:

Experimental procedure given in Table 28.

No. 2 Fuel Oil, Conveyor Speed, = 70.4 ft/min, Foam Wringing Pressure = 7.5 lb/in.

6.75-in. diameter roller.

Mulched foam loosely packed in 2-inch deep layer 2-feet wide.

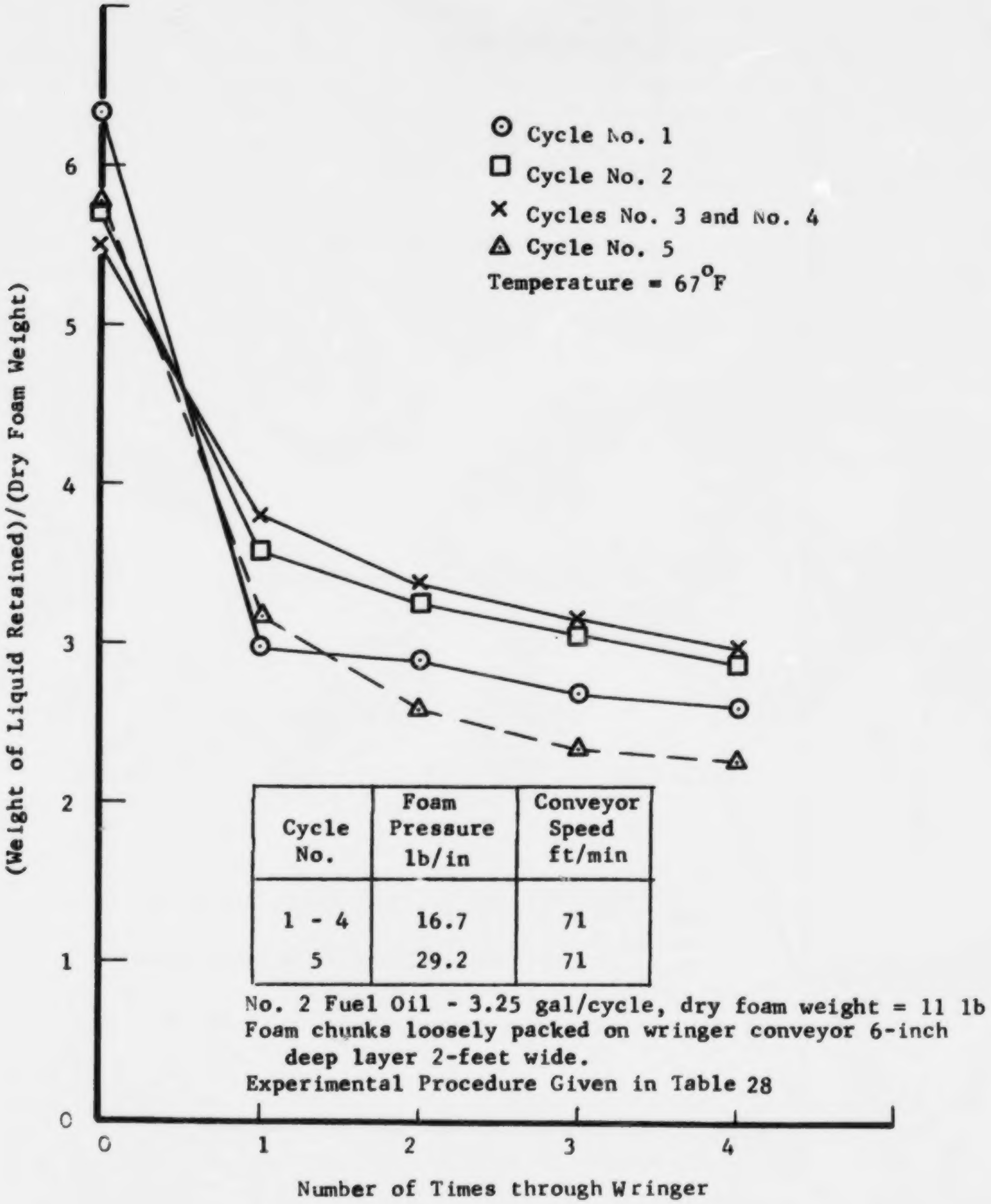
Wring No.	Liquid Removed (gal.) Oil	Water	Total	% Oil
1	2.1×10^{-1}	2.9×10^{-1}	4.9×10^{-1}	42
2	9.4×10^{-2}	1.1×10^{-1}	2.0×10^{-1}	47
3	5.7×10^{-2}	5.2×10^{-2}	1.1×10^{-1}	52
4	3.5×10^{-2}	3.5×10^{-2}	7.0×10^{-2}	50
5	2.1×10^{-2}	9.9×10^{-3}	3.1×10^{-2}	68
6	1.7×10^{-2}	1.5×10^{-2}	3.2×10^{-2}	52
7	1.0×10^{-2}	5.2×10^{-3}	1.6×10^{-2}	67
	4.42×10^{-1}	5.1×10^{-1}	9.5×10^{-1}	

For the experiments discussed above, the mulched foam was arranged in a 2-inch deep layer on the conveyor. As shown in the top photo of Figure 6, experiments were performed using the 24-inch diameter roller when the mulched foam was 6 inches deep. The results of these experiments are presented in Figures 78 and 79. The experiments were performed in exactly the same manner as described above except that the foam sample had a dry weight of 11 lb, and 3.25 gal. of oil were used for each cycle. The roller was fabricated from pipe having a 1/2-inch wall thickness, and the pipe plus the circular steel caps had a combined weight of 400 lb. For the first four cycles shown in Figures 78 and 79, the empty pipe was used as a roller, but for the fifth cycle the roller was partially filled with water and had a weight of 700 lb. With the roller completely filled with water, it weighed close to 1000 lb. Comparing Figure 77 and Figure 78, it is seen that the residual oil is approximately the same for the experiments performed with the 2-inch deep mulched foam layer and the 6 3/4-inch diameter roller as for the experiments performed with the 6-inch deep mulched foam layer and the 24-inch diameter roller. Comparing Figures 76 and 79, the transient process in which oil accumulates within the foam is similar for the two experiments.

Wringing Experiments with High Viscosity Oils

Wringing experiments were performed using mulched foam and high viscosity oils. The technique used is described in Table 28. Two experiments were performed, the first using 148 cs oil and the second using 1100 cs oil.

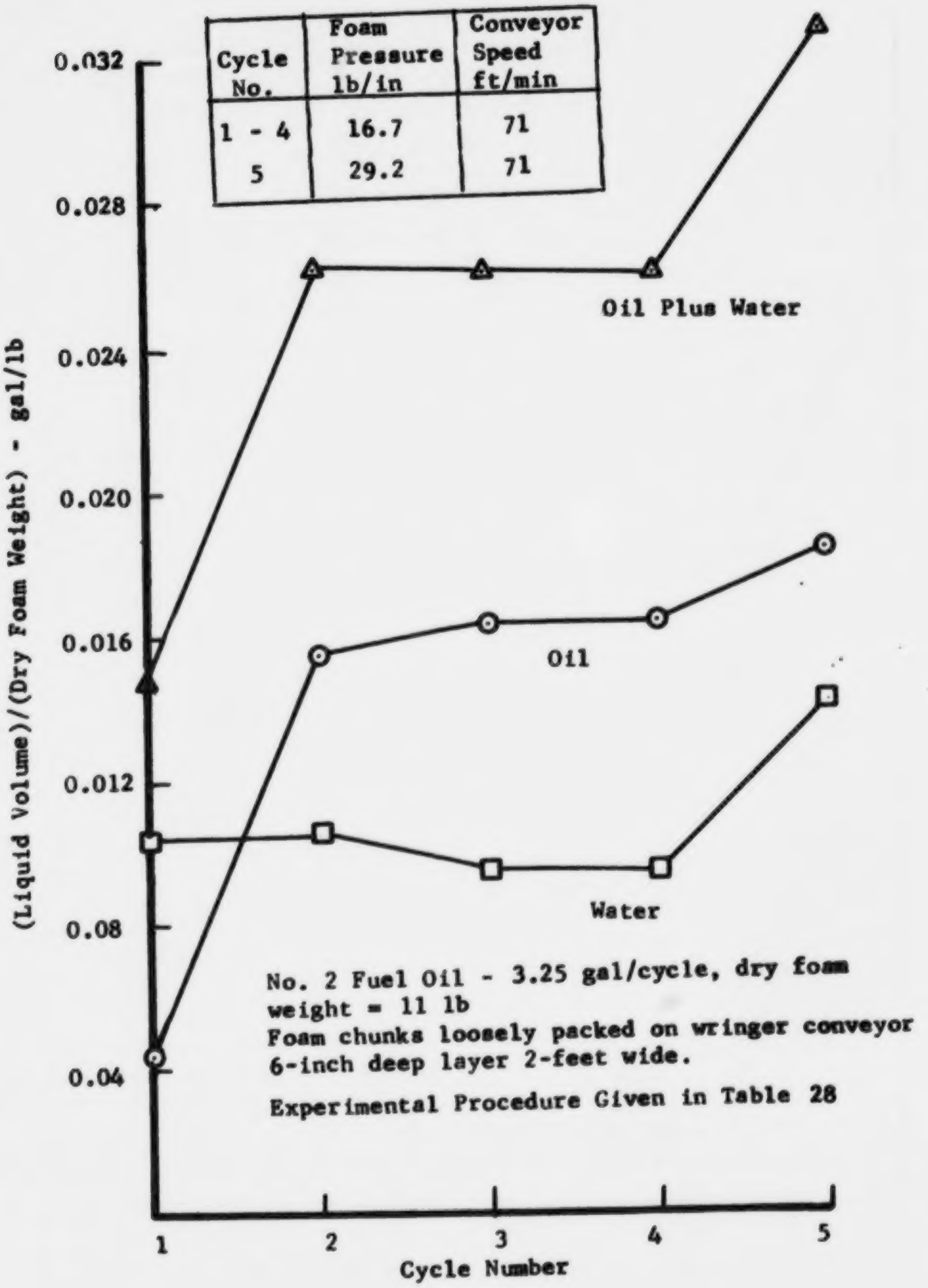
Table 30 gives the weight of the foam before and after wringing and the volumes of oil and water recovered for the two experiments. Table 31 shows



Cycle No.	Foam Pressure lb/in	Conveyor Speed ft/min
1 - 4	16.7	71
5	29.2	71

No. 2 Fuel Oil - 3.25 gal/cycle, dry foam weight = 11 lb
Foam chunks loosely packed on wringer conveyor 6-inch deep layer 2-feet wide.
Experimental Procedure Given in Table 28

FIGURE 78 - WRINGING PERFORMANCE USING 2-FT DIAMETER ROLLER



Cycle No.	Foam Pressure lb/in	Conveyor Speed ft/min
1 - 4	16.7	71
5	29.2	71

No. 2 Fuel Oil - 3.25 gal/cycle, dry foam weight = 11 lb
Foam chunks loosely packed on wringer conveyor
6-inch deep layer 2-feet wide.

Experimental Procedure Given in Table 28

FIGURE 79 - LIQUID REMOVED FROM FOAM USING 2-FT DIAMETER ROLLER

TABLE 30

BEHAVIOR OF FOAM DURING RECYCLING

Conditions:

Procedure given in Table 28.
Temperature = 55°F.
Conveyor Speed = 70.4 ft/min
Foam wringing pressure = 7.5 lb/in., three wrings/cycle, 6.75-in. roller.
Foam chunks loosely packed in 2-in. deep layer 2-ft wide.

Cycle No.	Initial Soaked Wt (lb)	Final* Wt (lb) After 3 Wrings	Weight Loss (lb)	Water Recovered (gal.)	Oil Recovered (gal.)	Oil and Water Recovered (lb)	Weight Not* Accounted For (lb)
Oil: 60% No. 6 Fuel Oil + 40% No. 2 Fuel Oil--148 cs, 2.2 lb dry foam, 0.65 gal of oil/cycle.							
1	20.9	14.7	6.2	5.0×10^{-1}	2.6×10^{-2}	4.4	1.8
2	23.9	15.0	9.0	4.2×10^{-1}	1.3×10^{-1}	4.6	4.4
3	24.9	15.0	9.9	7.5×10^{-1}	2.1×10^{-1}	8.1	1.8
4	23.8	15.0	9.0	4.7×10^{-1}	2.0×10^{-1}	5.7	3.3
Oil: 80% No. 6 Fuel Oil + 20% No. 2 Fuel Oil--1100 cs, 2.2 lb dry foam, 0.65 gal of oil/cycle.							
1	26.9	13.4	7.5	8.3×10^{-1}	2.6×10^{-2}	7.3	0.2
2	24.4	15.4	9.0	6.8×10^{-1}	3.9×10^{-2}	5.9	3.1
3	24.9	15.0	9.9	7.8×10^{-1}	6.5×10^{-2}	7.0	2.9

---

* Due to oil, water, and foam retained on conveyor and oil collection tray.

TABLE 31

WRINGING PERFORMANCE OF HIGH VISCOSITY OILS

Conditions:

Procedure given in Table 28.

Wringer pressure = 7.5 lb/in., 6.75-in. roller

Conveyor speed = 70.4 ft/min

2.2 lb dry foam, 0.65 gal oil/cycle

Foam chunks loosely packed in 2-in. deep layer 2 ft wide

Experiment No. 1 Oil Viscosity 148 cs - 60% No. 6 Fuel Oil and 40% No. 2 Fuel Oil at 55°F.

Cycle	Fluid Weight in Foam/Dry Foam Weight	
	Initial	After 3 Wrings
1	8.51	5.7
2	9.87	5.7
3	10.32	5.7
4	9.87	5.7

Experiment No. 2 Oil Viscosity 1100 cs - 80% No. 6 Fuel Oil and 20% No. 2 Fuel Oil at 55°F.

Cycle	Fluid Weight in Foam/Dry Foam Weight	
	Initial	After 3 Wrings
1	8.5	5.1
2	10.1	6.0
3	10.3	5.8

the weight of fluid in the foam divided by the dry foam weight before and after wringing. Comparison of the results presented here with those for the low viscosity No. 2 Fuel Oil presented in Figures 76 and 79 shows that the oil recovered is considerably less for the high viscosity oils. The fluid weight contained in the foam per weight of dry foam after wringing is 5.1 to 6.0 for the high viscosity oils versus 3.6 to 4.1 for the No. 2 Fuel Oil. This higher residual oil content is consistent, however, with the results presented in Table 25 for the experiments performed with the high viscosity oils and the foam cubes.

Wringing high viscosity oil from the foam can result in foam attrition. Figure 80 shows the effects of oil viscosity on the appearance of wrung foam. The experiments which produced these results were performed by wringing individual foam cubes soaked in oil with a wringing pressure much higher than that which would be encountered in the actual sorbent wringing system. These experiments illustrate the type of failure that can occur if the viscosity of the sorbed liquid(s) limits the rate at which it can flow out the foam pores in response to rapid application of wringer pressure.

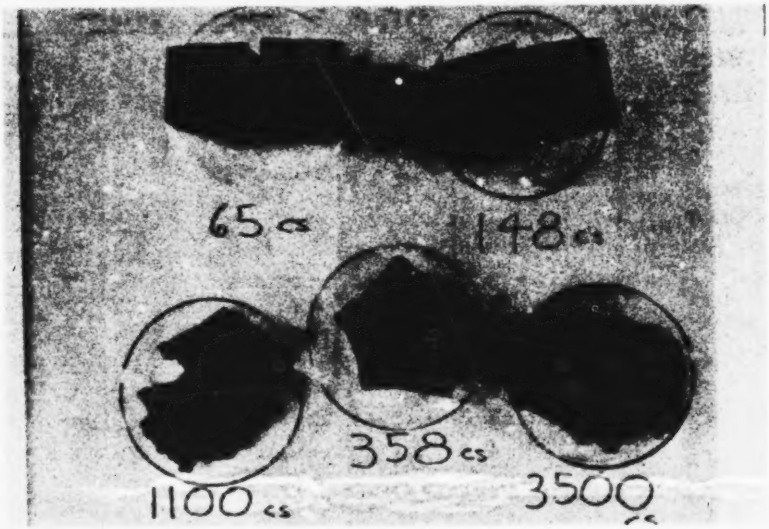


Figure 80 - FOAM FAILURE DURING WRINGING RESULTING FROM INCREASING OIL VISCOSITY

Wringing No. 2 Fuel Oil and water from mulched foam resulted in little or no attrition. A 2.2 lb sample was wrung more than 50 times with no noticeable attrition. However, for the experiments conducted using the high viscosity oils and the mulched foam, moderate foam attrition was observed.

Table 32 shows the mulched foam particle size distribution before and after wringing the indicated number of times. It appears that attrition of the large foam chunks (3" x 3" and 2" x 2") is the most severe, but that the smaller 1" x 1" foam chunks are better able to withstand wringing. If we assume that foam particles smaller than 1/2 " x 1/2" will not be recycled but removed from the sorbent stream on the work boat deck prior to redistribution, the data in Table 32 indicate that from 2% to 3% foam make-up per cycle would be sufficient to offset the attrition due to wringing for the highest viscosity oil tested.

TABLE 32

WRINGING ATTRITION OF MULCHED FOAM

Wringing Conditions:

Procedure given in Table 28.

Three wrings per cycle, wringer pressure on foam 7.5 lb/in., conveyor speed 70.4 ft/min, 6.75-in. diameter roller.

2.2 lb of dry foam, 0.65 gal oil/cycle.

Mulched foam loosely packed in 2-in. deep layer 2-ft wide.

	Foam Retained on Screen, Percent by Weight		
Screen Size	Initial Distribution	After 6 Cycles* Oil Viscosity - 148 cs	After 3 Cycles⁺ Oil Viscosity - 1100 cs
4" x 4"	0	0	0
3" x 3"	9.2	0	4.4
2" x 2"	50.0	11.3	23.5
1" x 1"	36.8	66.5	61.2
1/2" x 1/2"	3.5	19.4	9.3
Pass 1/2" x 1/2"	0.5	2.8	1.6

---

* 60% No. 6 Fuel Oil + 40% No. 2 Fuel Oil at 55°F

+ 80% No. 6 Fuel Oil + 20% No. 2 Fuel Oil at 55°F

Draining Rate from Mulched Foam

Table 33 presents the results from draining experiments. The experiments were conducted by confining foam in a two-foot by two-foot wire mesh box which was lifted from the oil covered water surface after the foam had been allowed to sorb oil and water for two minutes. Experiments were performed at two foam-water surface densities for the low viscosity No. 2 Fuel Oil. For these experiments the oil drained was always less than 3% of the total oil removed by both draining and subsequent wringing. For the more viscous oil, 5.3% of the liquid removed drained as the foam was lifted from the water.

TABLE 33

OIL DRAINED AS OIL-SOAKED FOAM IS LIFTED FROM WATER
(Initial Oil Slick Depth 0.06 In.)

Experimental Procedure:

1. Distribute foam uniformly over 2' x 2', 1" mesh wire box.
2. Lower box below oil covered water surface until the foam floats in the confined space formed by the sides of the box.
3. Allow the foam to sorb oil for 3 minutes.
4. Lift wire box from the water in approximately one second.
5. Collect effluent in a tray placed under the wire box.

Foam Surface Density (lb/ft^2)	Oil Viscosity (cs)	Oil Drained (gal.)	Oil Removed by Wringing (gal.)	Percent Oil Drained
0.13	4.0+	0.0026 to 0.0052	0.24	1.1 to 2.1
0.064	4.0+	0.0026 to 0.0039	0.16	1.6 to 2.4
0.16	148*	0.01	0.19	5.3

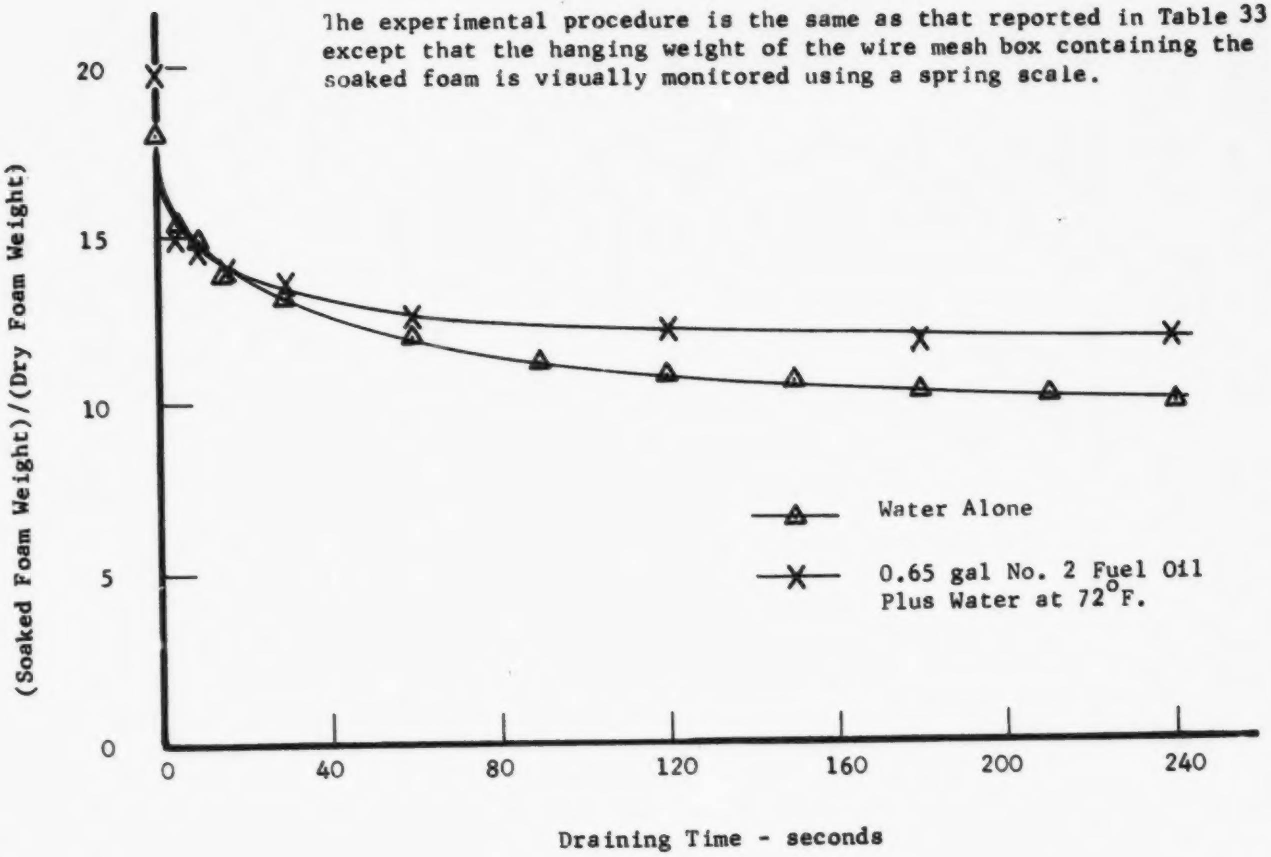
+ No. 2 Fuel Oil at 72°F.

* 60% No. 6 Fuel Oil + 40% No. 2 Fuel Oil at 72°F.

Figure 81 shows the rate at which liquid drains from the foam as it is pulled from the water. The 1.1 lb sample of mulched foam was confined by the two-foot by two-foot wire box to an approximate thickness on the water of two inches and was pulled suddenly from the water (removal time approximately one second). The rate at which the weight decreased during draining was observed. It is seen that more than 2/3 of the liquid which drains is removed in the first 40 seconds.

Oil Contamination in Water Removed by Wringing

The experiments summarized in Table 34 were performed to determine the oil content of the water separated from the wringer effluent. The experiments consisted of placing 0.65 gal of oil on the water surface. 2.2 lb of foam were added to the surface, allowed to soak oil, removed, and wrung three times. (For the detailed procedure see Table 28.) In all cases the oil/water mixture removed by wringing was allowed to separate by gravity for one hour prior to sampling the water phase. Visually, the separation was observed to cease after 15-30 min. All water samples were highly turbid, having a brownish hue which indicated they were highly contaminated. As shown in Table 34 the oil content varied from 630 to 1700 ppm indicating a need for additional treatment of the effluent water before it is discarded overboard.



The experimental procedure is the same as that reported in Table 33 except that the hanging weight of the wire mesh box containing the soaked foam is visually monitored using a spring scale.

FIGURE 81 - DRAINING RATE OF OIL AND WATER SOAKED FOAM

TABLE 34

OIL CONTAMINATION IN WATER REMOVED BY WRINGING

The wringing procedure used to collect the effluent is described in Table 28.

Test No.	Oil Used	Foam Used	Water Used	PPM Oil in Effluent
1	No. 2 Fuel Oil	Same used in sinking tests	Same used in sinking tests	980
2	No. 2 Fuel Oil	Same as No. 1	Clean	1700
3	Shallow Yates Crude Oil	New foam	Clean	1050
4	Shallow Yates Crude Oil	Same as No. 3	Same as No. 3	730

SECTION XII

FOAM DEGRADATION DURING RECYCLING

Introduction

It is expected that the cost of oil recovery will depend on the quantity of foam lost during each cycle. To identify sources of foam degradation during recycling, two test runs were made in which all parts of the system were operated in sequence through several cycles, and measurements were made of foam particle size distributions and foam losses at three points during each cycle. Different oils were used for the two test runs. The properties of the on-site generated polyurethane foams used in these tests are shown in Table 8.

Degradation Caused by Hay Blower

Prior to testing the total system, two runs were made to study particle size degradation of the polyurethane foam as a result of passage through the hay blower. One run was made with the beater chains installed (see Table 35). The beater chains caused progressive reduction in particle size with each successive pass. In the second run, the chains were removed after the first pass through the blower. Although some reduction in particle size was observed after the first pass, the rate of reduction was far less than was observed with the beater chains installed (compare Table 36 with Table 35).

Limited tests were made to explore the comminution of a higher tensile strength polyurethane foam for comparison with that used above. The material chosen was Scott Industrial Foam, polyester type, reticulated (Scott Paper Company, Chester, Pennsylvania) having a density of 1.98 lb/ft^3 and pore size of 64 ppi. Comparison of the properties of the sample used, shown in Table 37, with Table 9, show the Scott foam to have a tensile strength about seven times higher and compressive strength several times greater than that generated on site. Pore sizes and densities of the two foams are quite similar. Oil sorption tests indicated the two foams are comparable (see Tables 38 and 3).

Two runs were made with the Scott foam to study particle size degradation as a result of passage through the hay blower. One run was made with the beater chains installed (Table 39). Although some reduction in particle size was observed with multiple passes through the blower, the rate of reduction was far less than was observed with the foam generated on-site. (Compare Table 39 with Table 35). A second run was made with the beater chains removed after the first pass through the blower. As shown in Table 40, virtually no particle

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TABLE 35

PARTICLE SIZE DISTRIBUTION AFTER MULTIPLE PASSES OF ON-SITE GENERATED POLYURETHANE FOAM THROUGH REINCO HAY BLOWER--BEATER CHAINS IN PLACE

Screen Size, In.	Percentage of Foam Retained on Screen after Number of Passes Through Hay Blower			
	1	2	5	10
4 x 4	0	0	0	0
3 x 3	4.9	1.3	0	0
2 x 2	43.7	32.1	13.3	0
1 x 1	43.5	55.9	71.3	64.2
0.5 x 0.5	5.3	8.7	13.6	30.6
<0.5 x 0.5	2.5	2.0	1.6	5.2

TABLE 36

PARTICLE SIZE DISTRIBUTION AFTER MULTIPLE PASSES OF ON-SITE GENERATED POLYURETHANE FOAM THROUGH REINCO HAY BLOWER--BEATER CHAINS REMOVED AFTER FIRST PASS

Screen Size, In.	Percentage of Foam Retained on Screen after Number of Passes Through Hay Blower			
	1	2	5	10
4 x 4	0	0	0	0
3 x 3	14.0	11.7	2.9	2.4
2 x 2	47.8	45.7	40.9	26.4
1 x 1	32.1	34.7	47.1	56.8
0.5 x 0.5	3.7	4.1	5.0	7.9
<0.5 x 0.5	2.4	3.9	4.1	6.5

TABLE 37

PROPERTIES OF SCOTT INDUSTRIAL POLYURETHANE FOAM

Density, lb/ft^3	1.98
Pores/Inch	64
Tensile Strength, lb/in^2	23
Compressibility, $lb/50\ in^2$	
25% Compressed	39
50% Compressed	45
65% Compressed	55

TABLE 38

COMPARISON OF MAXIMUM OIL RETENTION BY POLYURETHANE FOAMS AFTER FIVE MINUTES DRAIN TIME WHILE SUSPENDED IN AIR

Test Conditions: Two-inch cubes of foam saturated with test oil prior to drain period. After draining, foam cube was weighed and then test oil was removed by successive washing with hexane, VM&P naphtha, and pentane, and then dried

Oil1)	Oil Held by Foam, lb/lb Foam1)	
	On-Site Foam	Scott
No. 2 Diesel	7.7	6.9
Blend	13.2	9.7
No. 6 Fuel Oil	30.4	27.6

---

1) See Tables 3 and 37 for properties.

TABLE 39

PARTICLE SIZE DISTRIBUTION AFTER MULTIPLE PASSES OF SCOTT INDUSTRIAL POLYURETHANE FOAM THROUGH REINCO HAY BLOWER--BEATER CHAINS IN PLACE

Screen Size, In.	Percentage of Foam Retained on Screen after Number of Passes Through Hay Blower			
	1	2	5	10
4 x 4	39.1	20.3	19.7	8.4
3 x 3	28.0	41.8	28.8	33.4
2 x 2	15.4	18.3	28.6	32.2
1 x 1	12.0	13.7	15.1	18.7
0.5 x 0.5	2.7	2.5	2.7	3.0
< 0.5 x 0.5	2.5	3.1	4.9	4.2

TABLE 40

PARTICLE SIZE DISTRIBUTION AFTER MULTIPLE PASSES OF SCOTT INDUSTRIAL POLYURETHANE FOAM THROUGH REINCO HAY BLOWER -- BEATER CHAINS REMOVED AFTER FIRST PASS OF FOAM THROUGH BLOWER

Screen Size, In.	Percentage of Foam Retained on Screen after Number of Passes Through Hay Blower			
	1	2	5	10
4 x 4	55.3	51.5	50.2	49.1
3 x 3	19.2	22.1	16.7	23.8
2 x 2	13.1	14.8	16.4	13.5
1 x 1	8.6	8.3	9.2	9.6
0.5 x 0.5	1.4	0.9	0.8	0.9
< 0.5 x 0.5	2.2	2.5	6.7	2.9

size reduction occurred after the first pass through the blower. These data show that higher tensile strength of the foam can significantly reduce the rate of comminution during distribution using a hay blower. Foam particle damage during wringing would be expected to be less than observed with the on-site foam, although no tests were made (see page 135 of Section XI). The Scott Industrial Foam is considerably more expensive than on-site foam (approximately $4.00 per pound vs 50¢ per pound for the on-site generated foam) and qualitative tests show the Scott foam will eventually become water saturated and sink when placed on quiescent fresh water. Thus the advantages of high tensile strength are not without compensating penalties.

Tests of Complete System

The equipment items used for tests of the system and the arrangement for the tests are shown in Figures 82 and 87. A sheet metal bin was used to transfer the mulched polyurethane foam to the hay blower, and a trough was provided on the hay blower to avoid loss by spillage. The sheet metal bin was weighed empty before the test and also when full of foam in order to ascertain the weight of foam used. Initial weight of dry foam was approximately fifty pounds for each run. The foam passed through the Reinco hay blower, equipped with beater chains for the first pass to mulch the foam. The beater chains were removed after the first pass so the unit acted only as a centrifugal blower. The blower discharged into a 16-inch sheet metal duct which conducted the mulched foam to a diffuser section designed to discharge the foam uniformly onto the surface of the current tank immediately downstream of where oil was being discharged onto the water surface. Water velocity in the current tank was adjusted so that the transit time on the water surface was approximately one minute. Oil was placed on the water in the current tank in a nearly uniform layer, approximately 0.04-in. thick, by use of a feed tank which discharged into a weir set across the current tank. An inclined board conducted the oil from the weir nearly to the water surface.

The harvester belt was set at an angle of 40° and adjusted to pick up the foam at about the rate of its arrival. Downstream of the harvester in the current tank was a 1/8-inch mesh screen which caught substantially all of the foam particles which by-passed the harvester. This foam was considered to be that which was lost from the system on each cycle.

The harvester dumped the foam onto a conveyor belt which in turn discharged into a chute which conveyed the foam to the wringer equipped with two 24-inch diameter rolls. The wringer discharged the "dry" foam back into the sheet metal bin and the liquids were pumped to a waste oil storage tank. The use of the 24-inch diameter rolls resulted in very high unit loading during wringing, which is a relatively severe test condition. No. 2 Diesel Fuel and a mixture of No. 2 Diesel Fuel (35%) and No. 6 Fuel Oil (65%) were used. These oils were chosen to given an indication of the effects of oil viscosity on foam particle

Figure 82 - FEEDING MULCHED FOAM FROM TRANSFER BIN INTO REINCO BLOWER

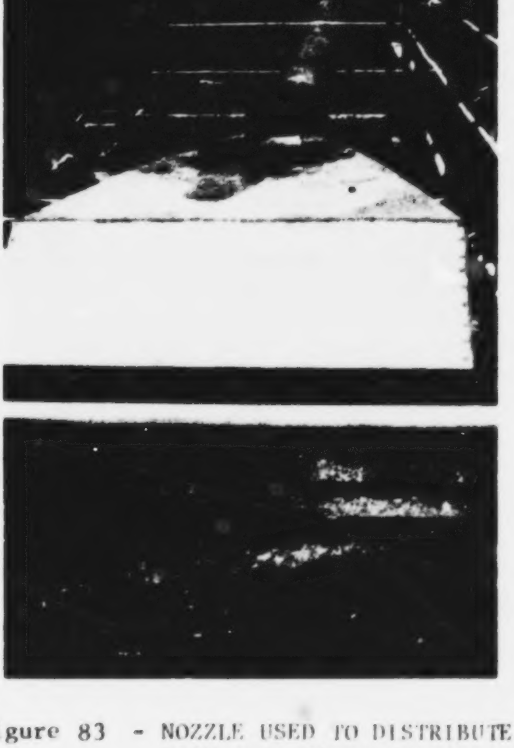

Figure 83 - NOZZLE USED TO DISTRIBUTE FOAM ONTO WATER SURFACE IN CURRENT TANK

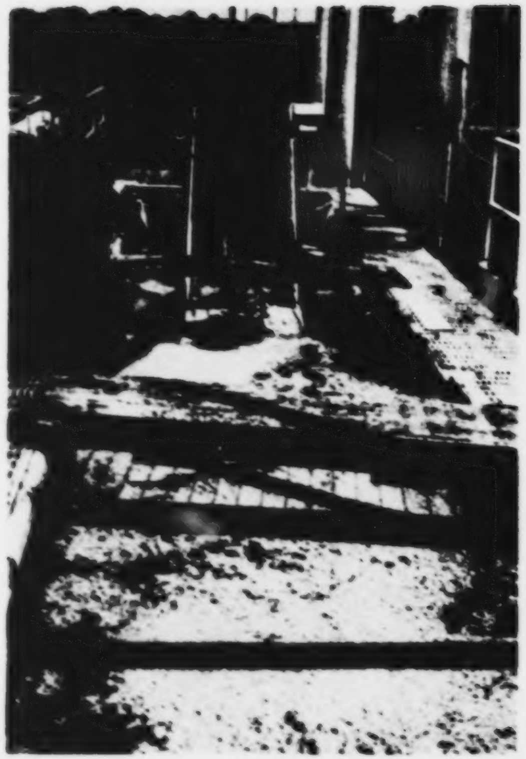

Figure 84 - FOAM APPROACHING AND BEING
PICKED OFF WATER SURFACE
BY HARVESTER BELT

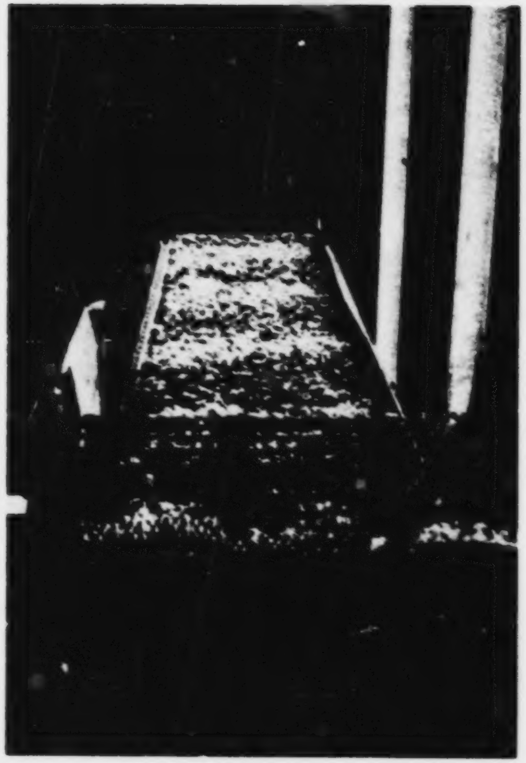

Figure 85 - HARVESTER BELT DISCHARGING
ONTO CONVEYOR BELT

Figure 86 - FOAM FALLING DOWN CHUTE ONTO LINK CHAIN BELT OF WRINGING APPARATUS. TWO 24-INCH ROLLS IN WRINGER

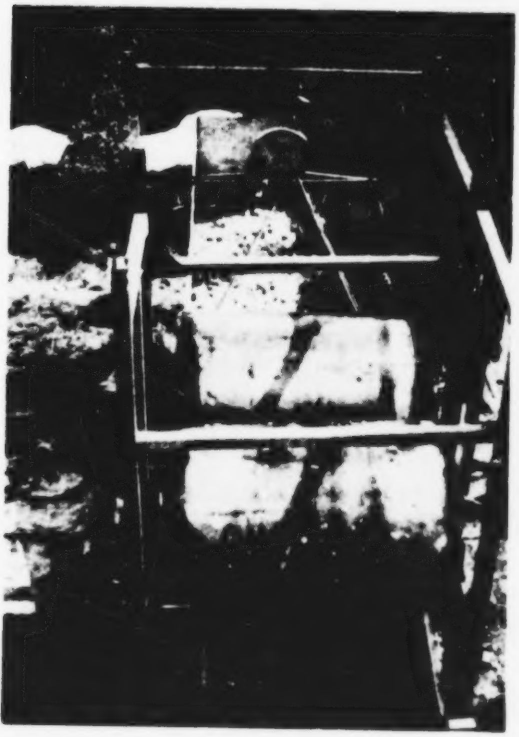

Figure 87 - WRINGER DISCHARGES DRY FOAM INTO TRANSFER BIN

size degradation. The viscosity-temperature relationships for these two oils are shown in Figure 88.

The tests were run until half of the original foam charge had been lost from the system. Particle size distribution of the foam was determined at three points in the system: after the hay blower, after the harvester, and after the wringer. Thief samples were taken at each location during each cycle of foam through the system and each sample was spread on a white board, photographed, and returned to the sheet metal bin. Particle sizes were measured visually from the photographs and counted to determine the particle size distributions.

The foam recovered from the current tank ("lost" from the cycle) was weighed after each cycle of each run. Because this foam was wet with both water and oil, one sample from each run was cleaned by washing with hexane, VM&P naptha, and pentane to remove the oil fraction and then dried overnight in a vacuum oven to remove the water. From this measurement the proportion of dry foam in the wet samples of "lost" foam was determined and the amount of foam lost during each cycle calculated. It should be noted that the foam lost from the system during each cycle included some which was not buoyant (no more than half of the total foam lost) and some which was basically buoyant but was nevertheless swept under the diversionary booms on the harvester or passed through the holes in the harvester belt.

Tests of foam degradation during re-cycling through the entire system were made using on-site generated foam produced on June 21, 1972 (see Table 8 for properties). As shown in Figure 89 over half of the foam was lost from the system within four cycles for the No. 2 + No. 6 Fuel Oil mixture and within five cycles for the No. 2 Fuel Oil alone. From these data, the rate of loss of foam is approximately eight to ten percent per cycle.

Foam was lost from the system partly due to comminution and partly due to loss of buoyancy, presumably because the few closed cells in the foam were ruptured. To identify the causes of comminution and foam loss, the particle size distributions measured at three points in the cycle (after passing through the hay blower, after the harvester, and after the wringer) are summarized in Tables 41 and 42. By comparison with the data in Table 36, which shows the effect of the blower alone on dry foam, it appears that passage through the whole system is more damaging to the foam than is passage through the blower alone. The largest single source of damage to the foam is believed to be the blower, but it appears that wringing partly tears the foam particles, making them more easily borken during subsequent passage through the blower. Particle size degradation appeared to be more severe with the more viscous oil (the No. 2 + No. 6 mixture). This is consistent with our earlier work on wringing, wherein we found severe damage to the foam particles at high oil viscosities (see Section XI).

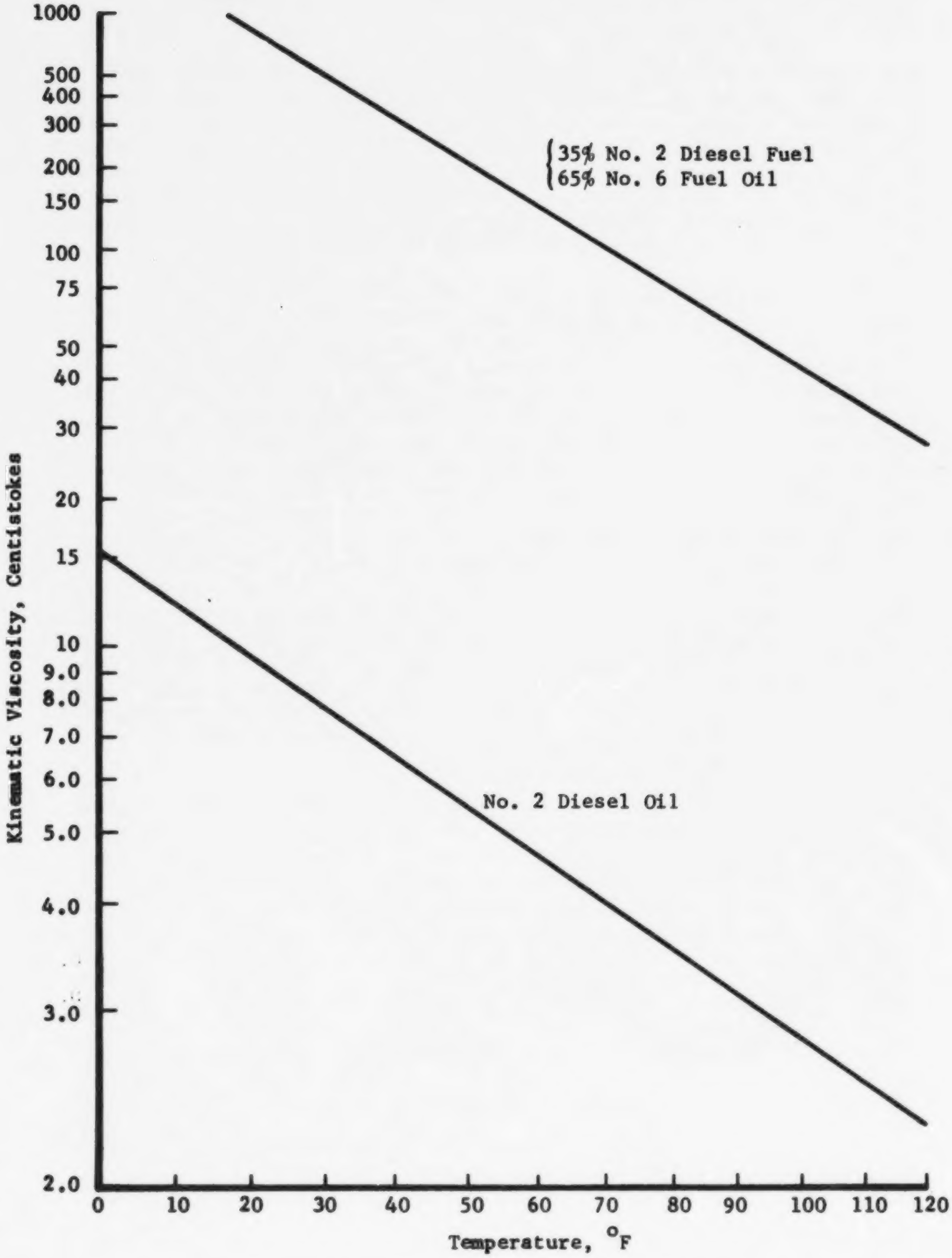

FIGURE 88 - VISCOSITY OF TEST OILS USED IN RECYCLING TESTS

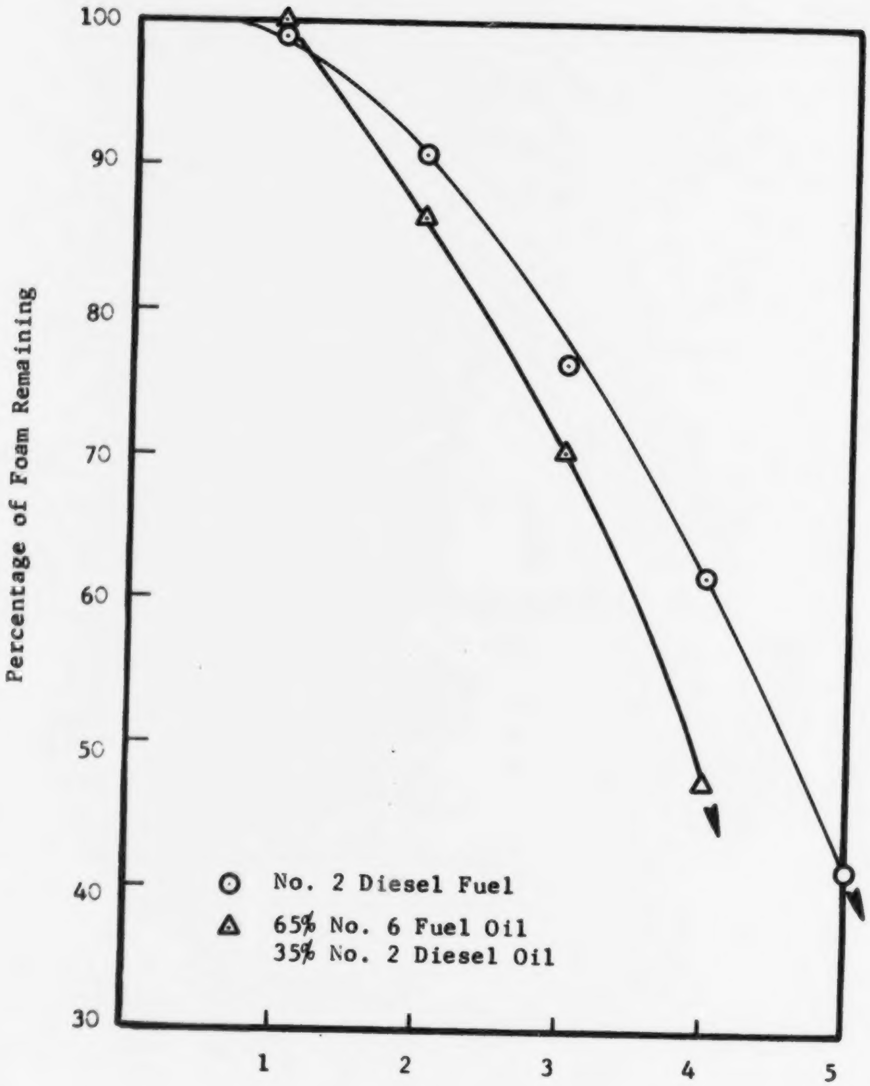

FIGURE 89 - POLYURETHANE FOAM REMAINING AFTER EACH CYCLE THROUGH SYSTEM

TABLE 41

PARTICLE SIZE DISTRIBUTION AFTER MULTIPLE PASSES OF ON-SITE GENERATED POLYURETHANE FOAM THROUGH WHOLE SYSTEM — TEST OIL: NO. 2 DIESEL FUEL

Screen Size, In.	Percentage of Foam Retained on Screen After Number of Cycles Through System				
	1	2	3	4	5
After Passage Through Blower					
> 4 x 4	6.4	0.0		0.0	0.0
> 3 x 3	42.1	23.0		0.0	0.0
> 2 x 2	38.2	38.6		20.0	0.0
> 1 x 1	12.6	35.5		45.9	32.7
> 0.5 x 0.5	0.7	2.8		24.2	37.2
< 0.5 x 0.5	0.0	0.2		10.5	31.5
After Harvester					
> 4 x 4	9.7	0.0		0.0	0.0
> 3 x 3	41.0	32.0		0.0	0.0
> 2 x 2	38.1	39.6		23.4	0.0
> 1 x 1	10.9	25.9		49.4	44.8
> 0.5 x 0.5	0.5	2.6		21.1	40.1
< 0.5 x 0.5	0.0	0.2		6.5	16.4
After Passage Through Wringer					
> 4 x 4	9.0	0.0	0.0	0.0	0.0
> 3 x 3	38.2	23.3	26.0	0.0	0.0
> 2 x 2	35.5	39.5	22.1	11.1	0.0
> 1 x 1	16.5	32.1	46.1	63.5	57.6
> 0.5 x 0.5	0.9	4.9	5.3	19.1	32.5
< 0.5 x 0.5	0.0	0.2	0.6	6.8	10.6

TABLE 42

PARTICLE SIZE DISTRIBUTION AFTER MULTIPLE PASSES OF ON-SITE GENERATED POLYURETHANE FOAM THROUGH WHOLE SYSTEM — TEST OIL: 35% NO. 2 DIESEL FUEL 65% NO. 6 FUEL OIL

Screen Size, In.	Percentage of Foam Retained on Screen After Number of Cycles Through System			
	1	2	3	4
After Passage Through Blower				
> 4 x 4	21.9	0.0	0.0	0.0
> 3 x 3	36.2	24.7	18.2	0.0
> 2 x 2	30.1	22.5	13.2	22.8
> 1 x 1	11.1	45.0	47.5	37.7
> 0.5 x 0.5	0.7	6.5	14.6	23.8
< 0.5 x 0.5	0.1	1.4	6.8	16.6
After Harvester				
> 4 x 4	10.8	0.0	0.0	0.0
> 3 x 3	56.2	46.2	0.0	27.3
> 2 x 2	26.0	37.2	24.7	39.9
> 1 x 1	6.9	15.4	48.6	31.7
> 0.5 x 0.5	0.1	1.3	25.8	1.4
< 0.5 x 0.5	0.0	0.1	1.5	0.1
After Passage Through Wringer				
> 4 x 4	36.9	0.0	0.0	0.0
> 3 x 3	34.8	7.7	12.3	0.0
> 2 x 2	22.1	47.9	40.0	57.8
> 1 x 1	6.2	41.9	42.9	39.8
> 0.5 x 0.5	0.2	2.8	5.0	2.6
< 0.5 x 0.5	0.0	0.0	0.1	0.1

SECTION XIII

FOAM DISPOSAL

Introduction

Techniques are needed to dispose of the polyurethane foam which has been used to sorb oil without creating additional pollution problems. The majority of our studies have concentrated on burning, though solution, compaction, and burial were also considered.

Disposal by Burning

Three separate thermal degradation studies were made to determine the effects of temperature on disposal of the on-site generated foam by incineration. Results of the first study showed that polyurethane foam can be fused to form a compact solid at a temperature of about 330°F to 350°F, indicating that the foam begins to melt and run at about 350°F.

A thermogram of the foam produced on November 2, 1971 (see Table 8) was made by measuring the weight loss as the temperature of the foam was continuously raised at 9°C per minute. The results are reported in Table 43 and Figure 90. The major portion of the polyurethane is vaporized at a temperature of about 800°C. The remaining 25% w appears to be carbon.

Mass spectrographic analyses of gases evolved from the November 2 foam at 200°C and 375°C were obtained. The analyses, reported in Table 44 show that ammonia and water were the only contaminants found that are not typical of normal, dry laboratory air. Weight loss versus sample temperature is shown in Figure 91. The weight loss at the outgas test conditions agrees reasonably well with the weight loss while constantly increasing the surface temperature at 9°C per minute as shown in Figure 90. These tests indicate the foam can be burned without the need for high ignition temperatures and further, that the burning operation not not hazardous.

A model furnace, is constructed after a limited literature search indicated commercially-available furnaces could burn a maximum of about 30%w plastic foam mixed with other combustibles (e.g., wood, paper, etc.). The model furnace used is pictured in Figure 7 and is shown schematically in Figure 92. Tests were made to evaluate this furnace for burning polyurethane foam. Dry, water wet, oil wet, and oil-water wet foams were burned. One pound lots of our standard foam were used to remove No. 2 Diesel fuel, Bunker C fuel and a one to one mixture of No. 2 Diesel and Bunker C fuels from water surfaces. Each lot of saturated foam was then passed through our model wringer three times to remove the excess oil and water. Immediately after wringing the foam was burned in the model furnace. A summary of the burning rates is shown in Table 45.

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TABLE 43

THERMAL DEGRADATION OF ON-SITE GENERATED POLYURETHANE FOAM

Sample Temperature °C	Sample Temperature °F	Weight Loss, %w	Elapsed Time Minutes
25	77	0	0
75	167	0	5
100	212	1	8
150	302	1	14
200	392	2	19
250	482	4	25
300	572	20	31
350	662	45	36
400	752	53	42
450	842	55	47
500	932	57	53
550	1,022	60	58
600	1,122	64	64
650	1,202	66	70
700	1,292	69	75
800	1,472	75	86
850	1,562	75	92

Notes:

1) Density of Foam, lb/ft^3 = 1.74
   Pores/Inch = 60
   Fusion Point, °F = 340
2) Temperature increased at 9°C per minute

TABLE 44

THERMAL HISTORY AND OUTGAS PRODUCT ANALYSES OF ON-SITE GENERATED POLYURETHANE FOAM[1]

Temperature,[2] °C	°F	Weight Loss %w	Elapsed Time, minutes	Comment
75	167	0	0	
150	302	1	12	
200	392	2	21	
200	392	5	51	Mass Spec. of Gas
250	482	7	59	
300	572	25	68	
375	707	40	80	
375	707	47	110	Mass Spec. of Gas
400	752	48	114	

---

1) Density of Foam, lb/ft³ = 1.74
Pores/Inch = 60
Fusion Point, °F = 340

2) Temperature increased at 6°C per minute

MASS SPECTROMETRY ANALYSES OF GASED SAMPLES AND NORMAL LABORATORY AIR

	Concentration, Mole %		
Outgas Composition	200°C	375°C	Normal Air (Dry)
N_2	68.10	74.61	78.08
O_2	25.26	23.17	20.95
H_2O	5.14	1.13	--
Ar	0.95	1.00	0.93
CO_2	0.52	0.07	0.03
NH_3	0.03	0.02	--

TABLE 45

POLYURETHANE FOAM BURNING RATE FROM FURNACE MODEL

Description of Foam	Burning Rate, Pounds of Dry Foam per Hour per Square Foot of Grate Area	Flame Temperature, °F	Stack Temperature, °F	Auxiliary Fuel Consumption SCF/Hr	Unburned Foam or Oil Lost as Dripping %w
Dry	36	1400-1500	1400-1500	42	Nil
Water Wet	14	1300-1400	1300-1400	42	Nil
No. 2 Diesel Wet	9	1400-1500	1400-1500	42	Nil
No. 2 Diesel Water Wet	15	1300-1400	1300-1400	42	Nil
Bunker C Water Wet	8	1200-1400	1200-1500	68	6
Bunker C, No. 2 Diesel Mix - Water Wet	14	1400-1500	1400-1600	68	1.5

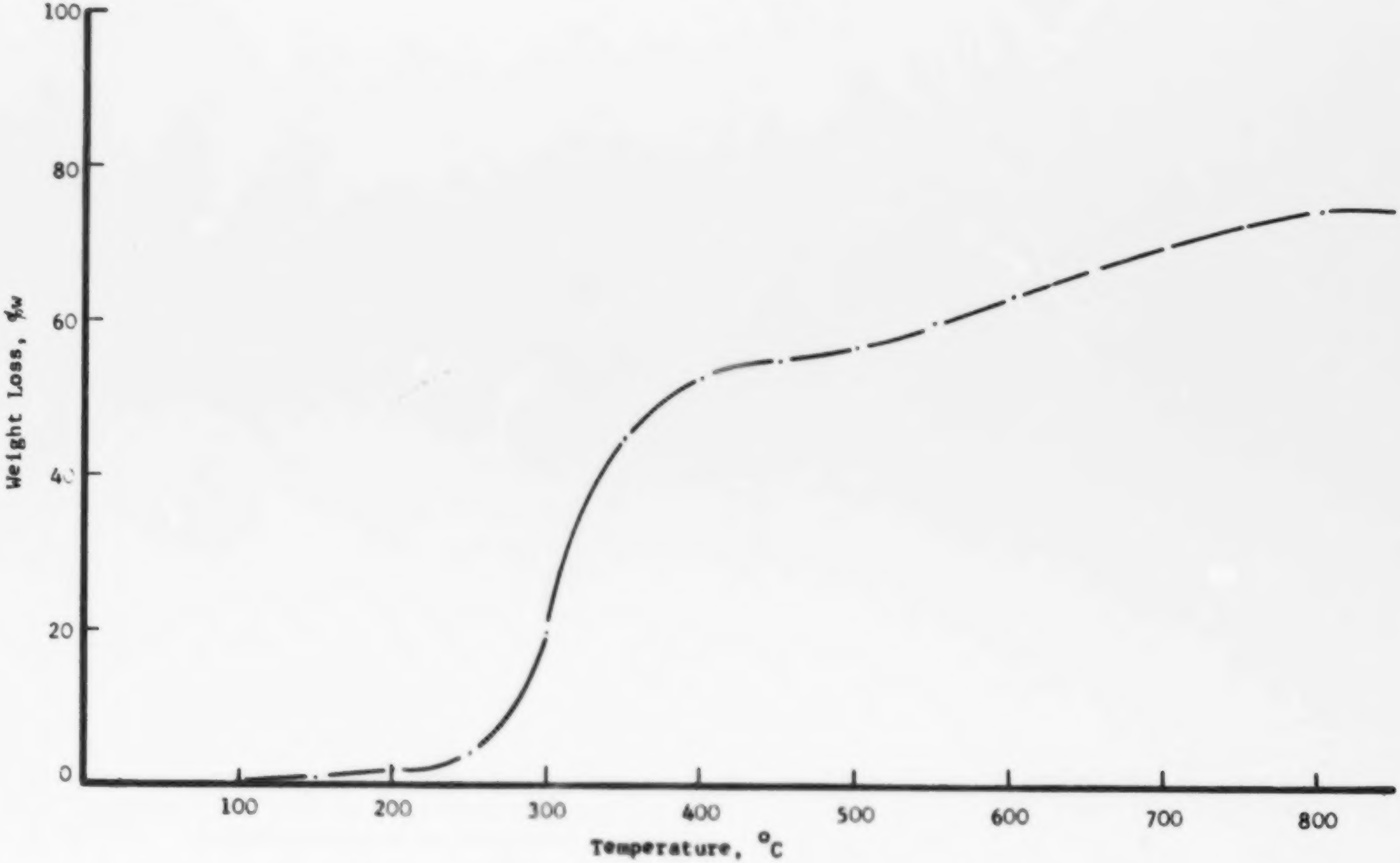


FIGURE 90 - WEIGHT LOSS VS SAMPLE TEMPERATURE - TEMPERATURE OF ON-SITE GENERATED POLYURETHANE FOAM INCREASED AT 9°C PER MINUTE

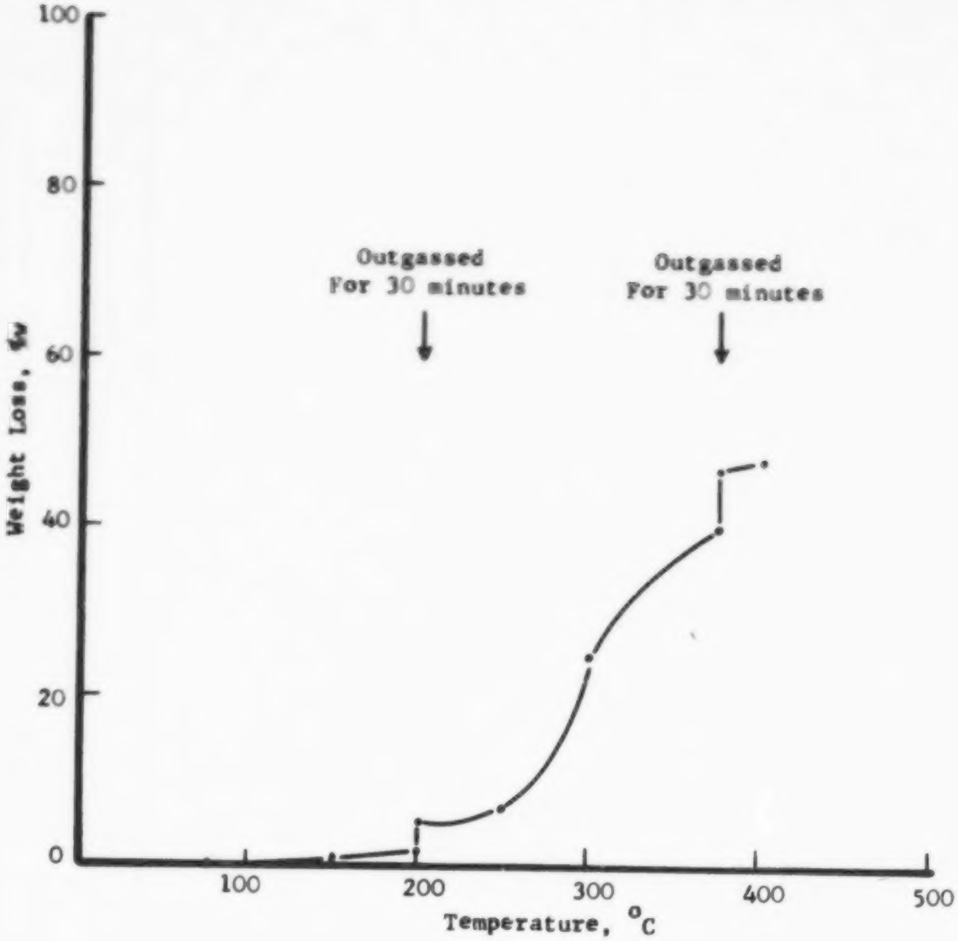


FIGURE 91 - WEIGHT LOSS VS SAMPLE TEMPERATURE - TEMPERATURE OF SHELL PIPE LINE POLYURETHANE FOAM INCREASED AT 6°C PER MINUTE

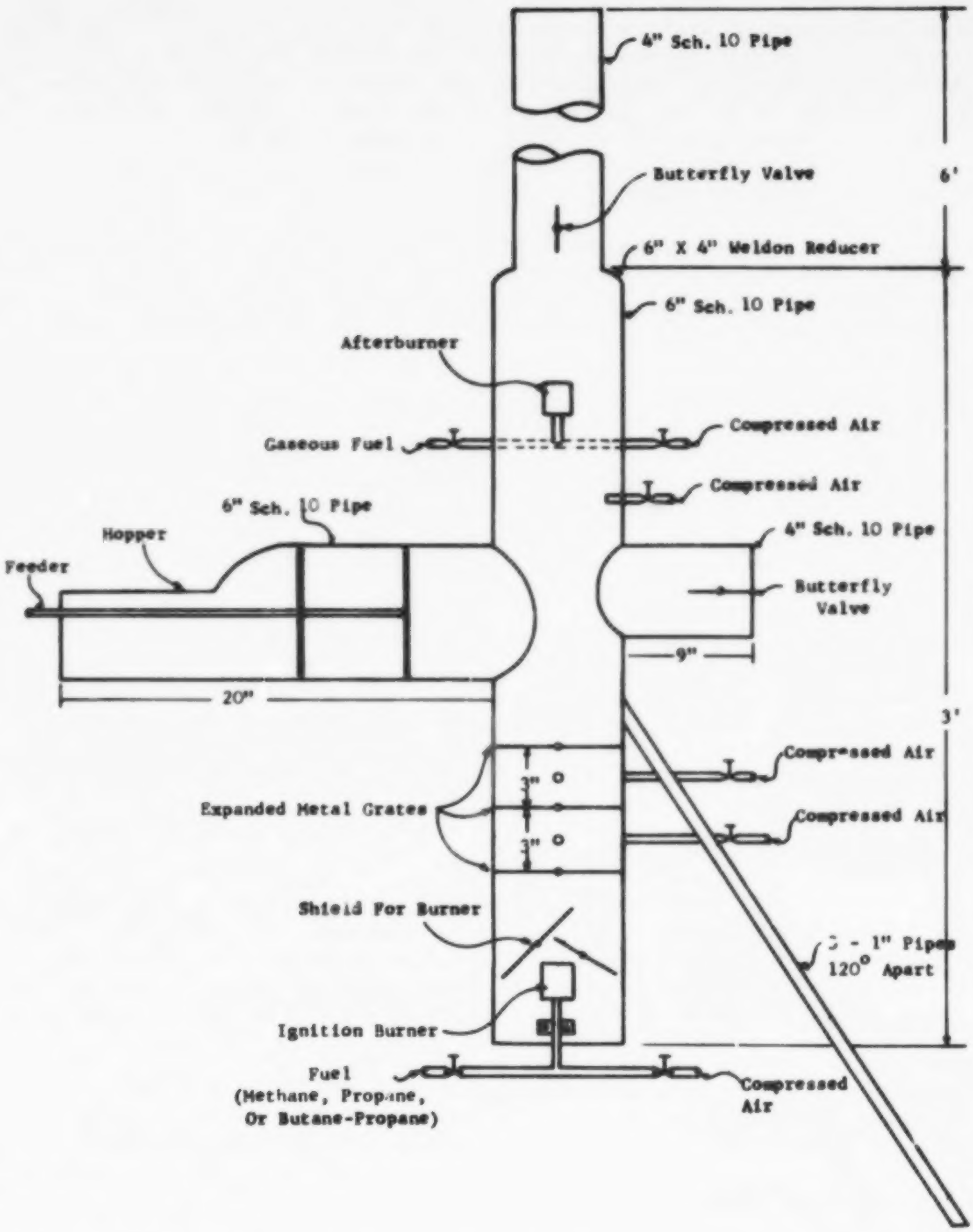

4" Sch. 10 Pipe
Butterfly Valve
6'
6" X 4" Weldon Reducer
6" Sch. 10 Pipe
Afterburner
Gaseous Fuel
Compressed Air
Compressed Air
6" Sch. 10 Pipe
Hopper
Feeder
4" Sch. 10 Pipe
Butterfly Valve
9"
20"
3'
Compressed Air
Expanded Metal Grates
3"
3"
Compressed Air
Shield For Burner
3 - 1" Pipes 120° Apart
Ignition Burner
Fuel (Methane, Propane, Or Butane-Propane)
Compressed Air

FIGURE 92 - POLYURETHANE FOAM BURNING FURNACE - SCHEMATIC

Bunker C-water saturated foam burned at about half the rate established for foam saturated with No. 2 Diesel fuel. More auxiliary fuel was also required, primarily in the afterburner, to prevent the emission of black smoke from the stack. Additionally, the Bunker C tended to drip past the three grates and out the bottom of the furnace. There is a possibility that incomplete combustion of foams soaked with heavy oils will also occur in a large furnace. A means to remove or recover the drippings may be necessary.

Water, added during burning or absorbed while sorbing oil from water, greatly reduced the particulate emissions. When either dry foam or oil-soaked foam is to be burned, water should be sprayed onto the foam prior to burning. The proper amount can be established by trial and error.

Injection of compressed air at various points, as shown in Figure 93, did not significantly improve either the burning rate or particulate emission rate. The use of forced draft air appears to be unnecessary. Flame and stack temperatures were low (Table 45) due in part to a large excess of air (Table 6). The water in the foam may also have been a factor. Temperatures in a large furnace may be higher, due in part to the smaller ratio of furnace surface area to burning grate area.

These burning tests indicate it is both practical and possible to construct a furnace at the site of an oil spill and to burn the used polyurethane foam without producing black smoke. The furnace may be constructed utilizing welders and normal work crews and readily available materials such as pipe, sucker rods, propane or butane burners, and air compressors. No scale-up problems are anticipated. A schematic of a large furnace is shown in Figure 93.

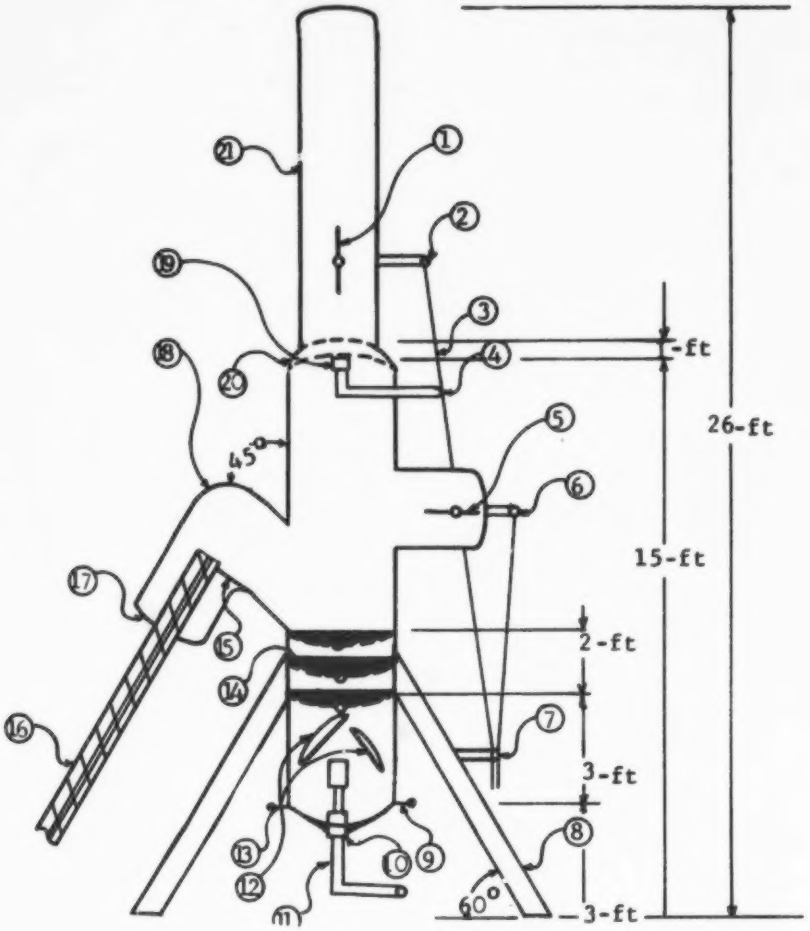
Disposal by Compaction and Subsequent Burial

Results from the fusion study show the polyurethane foam can be fused to form a compact solid at a temperature of about 330°F to 350°F. This indicates the volume of the foam could be reduced by heating it to the fusion point and compressing. The volume of dry foam can be reduced by a factor of about 30. The volume of oil-wetted foam can be reduced by a factor of about 10 (assuming the oil remains with the foam). Disposal by burial of compacted foam would require less volume of earth to be moved. Two major problems are envisioned if reducing the volume of used foam is necessary: 1) disposal of water and oil vapors, and 2) heat transfer to the core of foam particles.

Disposal by Solution

The on-site generated polyurethane foam is essentially insoluble or only slightly soluble in readily available solvents, e.g., aromatics, ketones, acetetes, glycol-ethers, chlorinated hydrocarbons, etc. For this reason, disposal by solution does not appear to be practical. Solubility tests

FIGURE 93 - SCHEMATIC OF SHELL PIPE LINE DESIGN POLYURETHANE FOAM BURNING FURNACE



1. Butterfly valve - secondary burning rate control (24-inch)
2. Butterfly valve - control handle
3. Butterfly valve - control rod
4. Afterburner fuel and air lines
5. Butterfly valve - air intake control valve (24-inch)
6. Butterfly valve - control handle
7. Butterfly valve - control rod latch
8. Pipe leg (12-inch)
9. Split slide valves - air intake control valves (36-inch)
10. Ignition burner mount for variable height burner
11. Ignition burner fuel and air lines
12. Ignition burner
13. Baffle plates to prevent foam dripping from affecting burner and to allow complete evaporation and combustion of foam drippings
14. Adjustable expanded metal grates
15. Shield to prevent foam from dropping out of feed inlet
16. Conveyer to feed used foam to furnace
17. Air intake annulus. Air keeps conveyer cooled and assists in carrying foam into furnace
18. Short radius 90° ell, 24-inch pipe fitting
19. Afterburner nozzle
20. Pipe furnace - 36 inch
21. Pipe stack - 24 inch

were made by placing 0.25 gram cubes of the on-site generated foam in 50 ml of each of the following solvents:

1. Benzene
2. Methylethylketone
3. Dichloromethane
4. Butyl cellusolve
5. Normal butyl acetate

None of these solvents dissolved a significant quantity of the foam in 240 hours.

SECTION XIV

SYSTEM DESIGN

Introduction - Offshore Systems

The initial concept of the offshore system, as shown in Figure 1, has been modified somewhat as a result of this study. While the original version is acceptable, the preferred offshore configuration is now represented by Figure 8. A smaller "half size" system, using the same equipment modules, is shown in Figure 9. The principal differences result from acceptance of a shorter residence time or slower system velocities, resulting in a more compact system requiring fewer vessels.

In the preceding sections (Section VI through Section XIII), all of the basic processes required for the oil spill cleanup system are described and characterized. Drawing upon these sections, the performance requirements for the system may be developed. There are essentially four steps in this procedure:

1. Establish the parameters of the design oil spill and the required rate of oil recovery.
2. Estimate material flow in the system to meet these requirements:
    - (a) Foam required
    - (b) Oil and water recovered
    - (c) Foam losses
    - (d) Foam for recycling
    - (e) Make up foam required
3. Estimate component performance requirements and approximate size.
4. Adjust components to satisfy overall system constraints as to mobility, vessel size, etc.

In this discussion, the above procedure has been used to develop the performance requirements for a system of the type shown in Figure 8. The sorption investigation has shown that, of the oils studied, the crude identified as Carnea 21 displayed the minimum specific sorption and effluent oil contents (see Figures 31 and 32). This oil, then, has been selected for preliminary design of a recovery system. In making this selection, and in applying the results of our laboratory sorption and separation studies, it is felt that a practical yet conservative design will be evolved. A system flow chart is shown in Figure 94. The following assumptions and estimates are based upon results in the earlier sections.

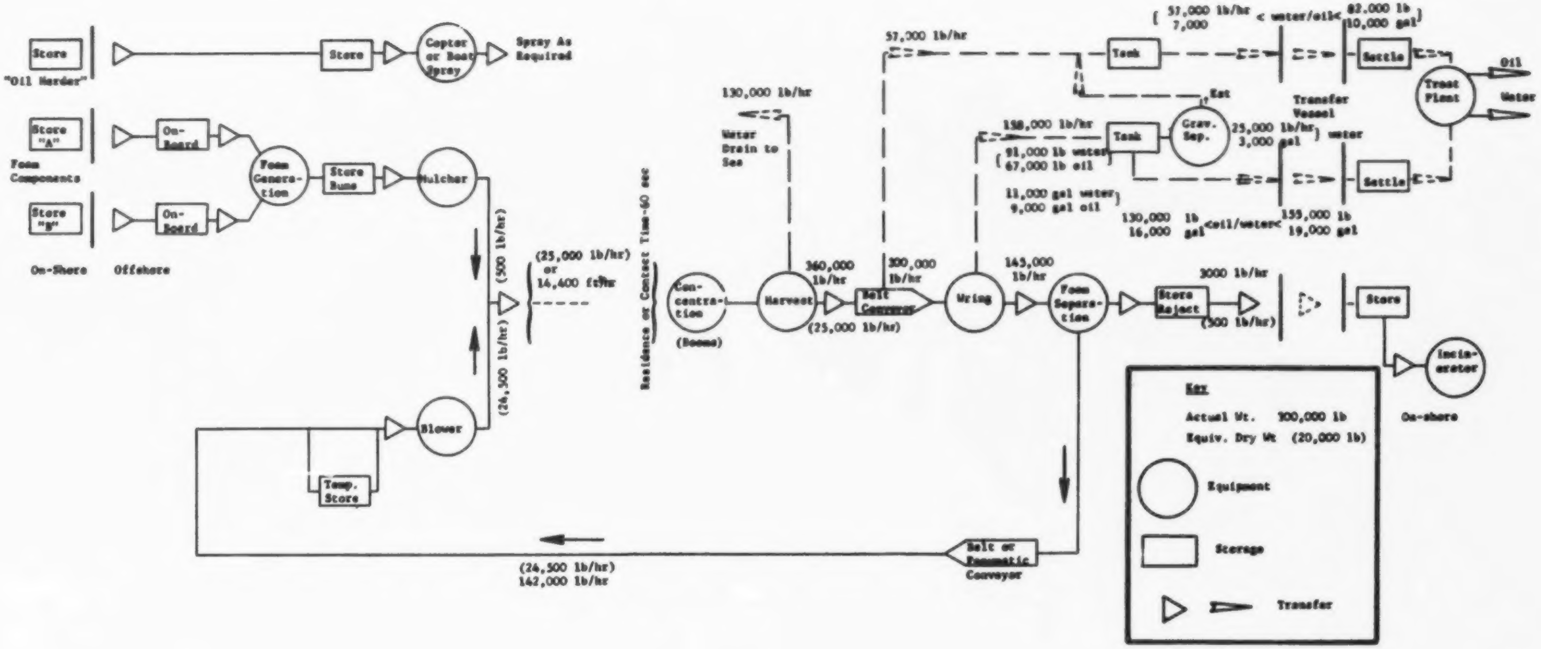

Store
"Oil Herder"
Store
Copter or Boat Spray
Spray As Required
Store "A"
Foam Components
Store "B"
On-Shore
Offshore
On-Board
On-Board
Foam Generation
Store Buns
Mulcher
Blower
Temp. Store
(500 lb/hr)
(24,500 lb/hr)
(25,000 lb/hr) or 14,400 ft³/hr
Residence or Contact Time-60 sec
Concentration
(Booms)
Harvest
130,000 lb/hr
Water Drain to Sea
360,000 lb/hr
(25,000 lb/hr)
Belt Conveyor
300,000 lb/hr
57,300 lb/hr
Wring
158,000 lb/hr
91,000 lb water
67,000 lb oil
11,000 gal water
9,000 gal oil
143,000 lb/hr
Foam Separation
Tank
Tank
Grav. Sep.
Ext
25,000 lb/hr
3,000 gal
water
57,000 lb/hr
7,000
< water/oil<
82,000 lb
10,000 gal
Transfer Vessel
130,000 lb
16,000 gal
<oil/water<
155,000 lb
19,000 gal
Settle
Settle
Treat Plant
Oil
Water
Store Reject
3000 lb/hr
(500 lb/hr)
Store
Incinerator
On-shore
Belt or Pneumatic Conveyor
(24,500 lb/hr)
142,000 lb/hr
Key
Actual Wt. 300,000 lb
Equiv. Dry Wt (20,000 lb)
Equipment
Storage
Transfer

FIGURE 94 - FLOW CHART PROTOTYPE - EXAMPLE

Oil Recovery System Using Sorbent Materials
Polyurethane Foam - Generated On-Site

System Requirements - Assumptions

-- Oil: Carnea 21, specific gravity = 0.889, viscosity = 31 cs at 70°F.

-- Spill: 0.06 in. (1.5 mm) thick

-- Recovery specified: 9000 gal./hr oil (this equates to 240,000 ft^2/hr of spill that must be traversed).

-- Sorbent: Foamed on-site polyurethane foam, average density 2.1 lb/ft^3.

-- Characteristics of foam application:
  Residence time: 60 sec (min)
  Specific oil recovery: 0.35 - 0.41 gal./lb
  Effluent: 45 to 50% oil
  Residual oil in foam after wringing: 0.47 - 0.48 gal./lb
  Foam concentration on surface of spill: 0.1 lb/ft^2(max)

Material Flow - Estimates

-- Foam Required:

$$\frac{9000\ \text{gal.}}{\text{hr}}\ (\text{oil}) \times \frac{\text{lb (foam)}}{0.35\ \text{gal. (oil)}} = 26{,}000\ \text{lb/hr}$$

(This is approximately 12,000 ft^3/hr)

-- Oil and Water Recovery:

		Time	Unit Quant.	Total
a.	Foam at contact with harvester	0 sec	34 lb/ft^3	490,000 lb/hr
b.	Foam at transfer to deck conveyor	10 sec	25 lb/ft^3	360,000 lb/hr
c.	Water drained to sea		(9 lb/ft^3)	(130,000 lb/hr)
d.	Foam at approach to wringer roll	30 sec	21 lb/ft^3	300,000 lb/hr
e.	Water/oil drain to storage		(4 lb/ft^3)	(57,000 lb/hr)
f.	Fluid removed by wringing			

Oil (45%) at 0.35 gal./lb = (4.6 lb/ft^3)(67,000 lb/hr)
Water = (6.3 lb/ft^3)(91,000 lb/hr)
Total fluid removed = (10.9 lb/ft^3)(160,000 lb/hr)

g. Foam at exit

Total weight = (21 - 10.9) lb/ft^3 = 10.1 lb/ft^3

Foam weight = 1.74 lb/ft^3

Residual liquid = (8.3 lb/ft^3)

(Note that this calculated residual of 8.3 lb/ft^3 is in rough agreement with the 6.3 lb/ft^3 determined in some experiments.)

-- Anticipated Foam Losses (distribution, collection, harvesting, wringing, etc.) ≤ 10%

Dry wt. equiv. = 25,000 lb/hr; actual = 15,000 lb/hr ±

-- Foam available for recycle
From above, 90%
dry equiv. = 25,000 lb/hr; actual = 140,000 lb/hr

-- Make up foam requirement
From above, 10% ±, or 2,500 lb/in.

System Components

Single Barge/Single Boom Configuration

Having values given for slick thickness, area covered per hour, and residence time; combinations of system velocity, boom length, and boom deployment angle may be investigated. Such an exercise is represented in graphical form in Figure 95.

Entering the top portion of Figure 95 with thickness and a system velocity

d_s = 0.06 in., V_s = 2.0 ft/sec

it is seen that the opening in the boom array (the swept width $\overline{W}$) must be at least 27 feet. Continuing to the lower portion of Figure 101, to the velocity of 2.0, it is seen that a boom 125 feet in length, deployed at about 15 degrees, will be satisfactory.

However, for this example involving a larger barge, a higher velocity might improve handling characteristics; for instance, a velocity of 3.0 ft/sec with a sweep of 23 feet and a 180-foot boom would serve.

Concentration of Foam by Booms

In sizing equipment, it is convenient to consider the material flow per unit width - Q', where:

$Q' = D \times V_s \times 3600$

Q' = lb/hr-ft

D = Foam concentration lb/ft^2 (or, area density)

V_s = System velocity - ft/sec

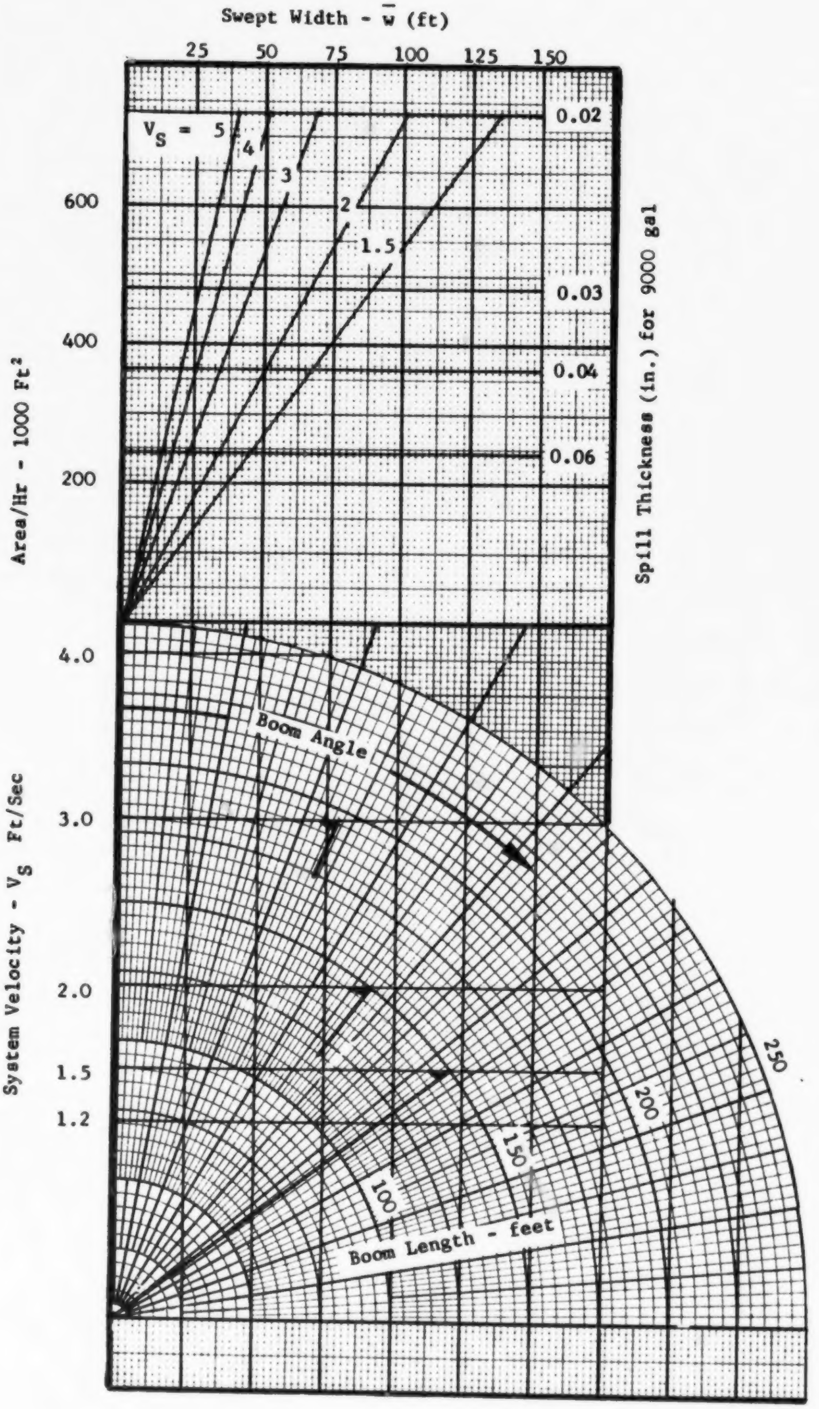


FIGURE 95 - MINIMUM BOOM REQUIRED FOR SINGLE BOOM SYSTEM WITH 60 SECOND FOAM RESIDENCE

This expression has been graphed in Figure 96.

For the example, the foam entering the boom array is calculated:

$$Q' = 0.1 \text{ lb/ft}^2 \times 3.0 \text{ ft/sec} \times 3600 \text{ sec/hr}$$
$$= 1100 \text{ lb/hr-ft}$$

(This quantity can also be found from Figure 96)

As the foam is further concentrated in approaching the harvester, Q' is modified by the width ratio $\overline{W}/w$, where w = width of harvester belt.

Harvester Width and Operation

Experiments have shown that the foam, when driven onto a conveyor by water motion, will pack to a density (apparent) of from 4.0 to 6.3 lb/ft^3 (dry foam equivalent). For sizing a harvesting conveyor, a conservative value of 4.1 lb/ft^3 has been used as a "design" value (see explanation of the relationship between Q'_H and belt speed V_B for various packing thicknesses in Section X).

Since conservative mechanical design limits flat belt conveyor speeds to four or five ft/sec, and since normal practice would be to operate the belt at:

$$V_B = V_s/\cos\theta$$

where θ = angle of inclination,

where $\theta = 40^\circ$,

$$V_B = 3.9 \pm \text{ ft/sec}$$

at

$$V_s = 3.0 \text{ ft/sec}$$

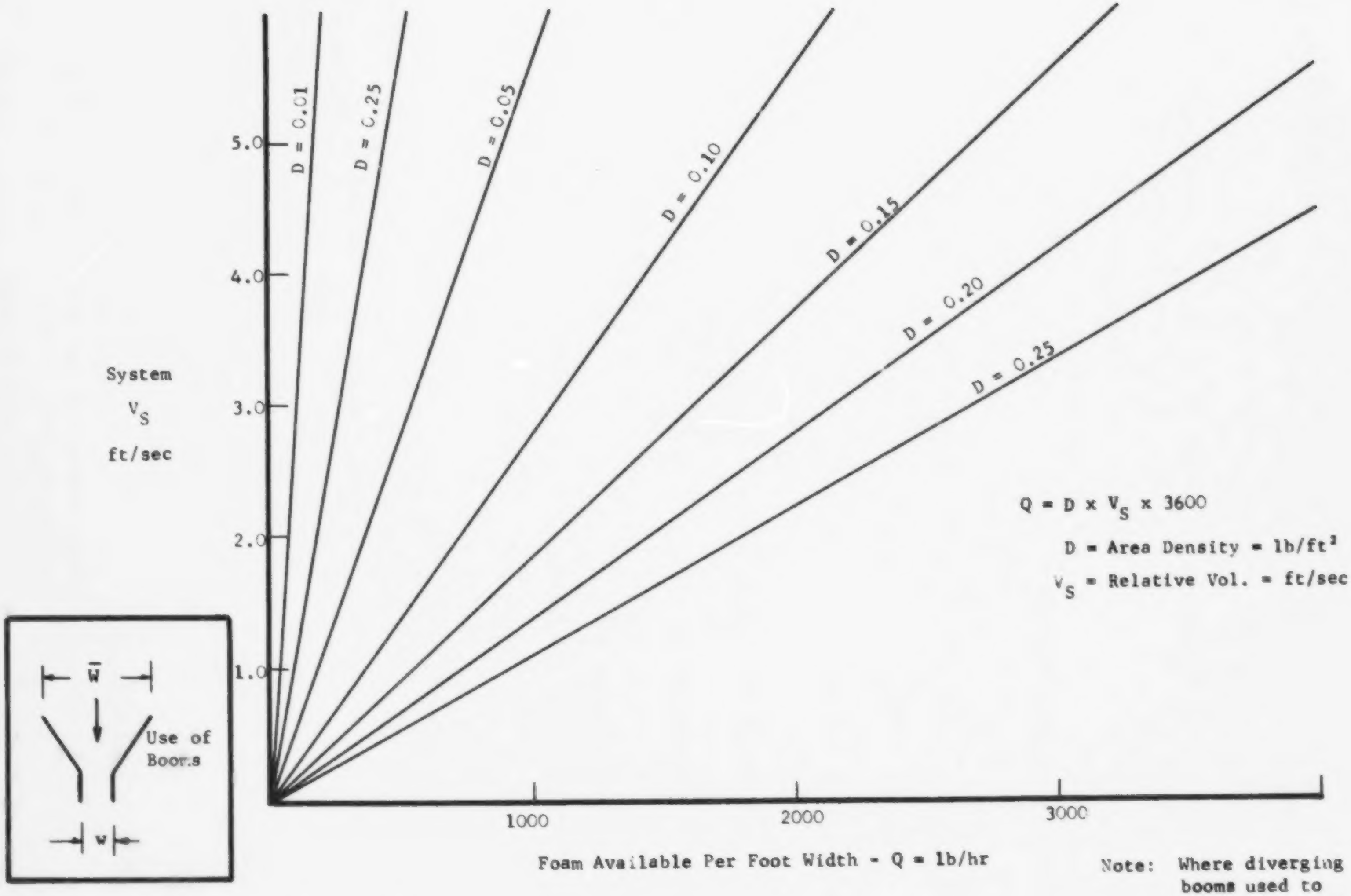
The figures may be used to estimate the foam thickness for various harvester widths, resulting in a width selection (tentative design of harvester has been based on a maximum foam thickness of about 0.2 ft, although higher values are practical). The equation developed in Section X

$$Q'_H = (d_{s_{avg}})(V_B)(3600)(4.1)$$

where $d_{s_{avg}}$ = avg thickness - ft may be used to find a practical value of harvester width w by trial and error:

$\overline{W}$	w	$\overline{W}/w$	$Q'_{\overline{W}/w}$*	d_s	V_B
23	15	1.5	1700	0.05	2.2
				0.08	1.5
23	10	2.3	2600	0.05	3.4
				0.08	2.3
				0.10	1.7
23	5	4.6	5100	0.30	4.8
				0.40	3.6

* $Q'_{\overline{W}/w} = (\overline{W}/w)(1100)$



$Q = D \times V_S \times 3600$

D = Area Density = lb/ft^2

V_S = Relative Vol. = ft/sec

Note: Where diverging booms used to concentrate foam. Multiply Q by ratio $\bar{W}/w$.

FIGURE 96 - FOAM AVAILABLE TO HARVESTER PER UNIT WIDTH

A five-foot width would exceed the d_s and V_B limitations; a 10-foot width is satisfactory and capable of handling surges in flow.

Wringer Feed Conveyor

The foam being transferred from the harvester to the wringer has drained some 10-20 seconds while on the harvester. Experiments have shown that this material, when dropped onto a belt, will pack to an apparent density of about 2.0 lb/ft³ (dry foam equivalent). The basic equation is modified:

$$Q' = (d_{s_{avg}})(V_B)(3600)(2.0)$$

The wringing experiments have shown that foam thicknesses of 0.5 ft and belt speeds of 100 ft/min (1.7 ft/sec) are acceptable for a simple cylindrical roller. At these values, an indicated minimum belt width would be found as

$$Q'_F = (0.5)(1.7)(3600)(2.0)$$
$$= 6000 \text{ lb/hr-ft}$$

$$\text{and the width} = \frac{25{,}000 \text{ lb}}{\text{hr}} \times \frac{\text{hr-ft}}{6020 \text{ lb}} = 4.2 \text{ ft}$$

To allow for surges caused by irregular flow, a greater width would be advisable.

Transfer After Wringing

If a belt conveyor is used for part of the foam recycling operation, its size will depend again upon an experimentally determined apparent packing density, found to be about 1.6 lb/ft³ (dry foam equivalent). The flow equation is again modified:

$$Q' = (d_{s_{avg}})(V_B)(3600)(1.6)$$

If a width is arbitrarily selected to match that of the other modules, say 5 feet, a belt speed is assumed and the average thickness found:

$$Q' = \frac{25{,}000}{\text{hr}} \times \frac{1}{5\text{ft}} = \frac{5{,}000 \text{ lb}}{\text{hr-ft}}$$

a reasonable velocity of 3.0 ft/sec gives:

$$d_{s_{avg}} = \frac{5{,}000 \text{ lb/hr-ft}}{3.0 \text{ ft/sec} \times 3600 \text{ sec/hr} \times 1.6 \text{ lb/ft}^3} = 0.28 \text{ ft}$$

Storage of Liquids

It is proposed that liquids be stored temporarily on deck, either in bolted steel storage tanks or in fabric storage cells. No attempt is made to provide separation of water on board except that a two-stage liquid system could by employed where conveyor drain and gravity settling in tanks might permit segregation of liquid containing little oil. Multiple tanks in battery, with suitable manifolding, would give this flexibility.

On a large, stable barge or in protected waters, the conventional oil-field bolted steel tanks could be utilized in capacities from 250 bbl (10,500 gal., 8 ft high x 16 ft diameter) to 1000 bbl (42,000 gal., 8 ft x 30 ft diameter, or 16 ft x 21 ft diameter). These tanks are available palletized for storage and are usually fabricated in accordance with API Standard 12B.

Estimated weight on pallets: 0.3 - 0.5 pounds /gal. cap.
Estimated cost on pallets: 12-15 cents/gal. cap.
Assembly time: 12 hours or more.

On any vessel, and particularly where assembly time is critical, the fabric containers would be recommended. In most cases, careful attention to tie-down provisions will be necessary but this should not be a problem on a steel vessel. Less efficient use of deck area is achieved, but ease of installation and convenience in storing tend to offset this. Consideration should be given to providing a mix of 20,000 gallon and, perhaps, 10,000 gallon sizes to facilitate installation. Typical sizes and estimated costs for the usual fabric oil storage container are:

20,000 gallon: 28 ft x 28 ft x 4 ft high

Shipping crate: 410 lb
5 ft x 4 ft x 2 ft

Unit weight: 0.02 lb/gal. cap.

Est. unit cost: 25-30 cents/gal. cap. (including special tie down straps)

10,000 gallon: 20 ft x 20 ft 4 ft high

Shipping crate: 260 lbs
5 ft x 4 ft x 1 ft

Unit weight: 0.026 lb/gal. cap.

Est. unit cost: not estimated

Adjust Component Designs to Suit System Requirements

To arrive at a preliminary system design that will satisfy the performance requirements, be modular in configuration, and be adaptable to convenient transport and assembly, the components described in the foregoing may be modified. Such adjustments at this stage are somewhat arbitrary and a matter of judgment.

To provide for the modular concept, provide a certain amount of redundancy as well as surge capacity, components may be somewhat oversized. When the basic performance estimates are also somewhat conservative, it is probable that the system described in this example is, indeed, oversized.

To review the example calculations of the preceding pages, both the material flow chart of Figure 94 and an estimate of the material inventory will be useful. Once the system has reached its full operating condition, the total throughput of foam (dry weight equivalent) is 25,000 lb/hr, of which about 2,500 lb/hr will be lost from the stream of useful sorbent, (see Section XII), requiring a like capacity for manufacture and introduction of new foam. This make-up rate is well within the capacity of the commercial scale foam generators and the single large size mulcher (Section VIII). During startup of the system, it would not be necessary to manufacture and mulch at the overall throughput rate, since it is only necessary to introduce an amount equal to the inventory required for a single cycle.

The foam inventory may be estimated from the assumed or calculated throughputs in the example. Allowing for variations and surges, we estimate the length of time required for one complete cycle to be:

Residence on the surface	60 - 120	seconds
Time on harvester	10 - 15	seconds
Wringer feed conveyor	10 - 40	seconds
Wring and separate	5 - 10	seconds
Recycle by belt conveyor	65 - 80	seconds
Total cycle time	150 to 265	seconds

Then, without consideration of storage in the cycle, the foam inventory is found:

Foam inventory = 25,000 lb/hr x hr/3600 sec x 150 sec = 1000 lb (min)
and the larger estimate = 1800 lb (max)

To allow for short interruptions of, say, no more than two minutes in the recycling process, the foam inventory might be selected as 1800 lb. A summary review of the system in this example results in the following:

- Foam throughput: 25,000 lb/hr, 420 lb/min, 14,000 ft^3/hr
- Foam inventory in system: 1800 lb
- Foam manufacture: One commercial unit: 2500 lb/hr
- Foam preparation: One Reinco Model M60-F6: 5-6,000 lb/hr
- Foam initial distribution: above mulcher: 6000 lb/hr
- Boom: single boom, 180 feet ± with 23-foot opening
- Harvester: twin 5-foot wide flat belt modules, each 33 feet ± long
- Wringer feed and wringer: twin metal belt 5-foot modules with dual cylindrical rolls
- Recycle belt conveyor: single 5-foot fabric belt conveyor, in sections for total length of approximately 200 feet (NOTE: The pneumatic systems described in Section VIII would be preferred and are indicated in the figures).

-- Foam storage for shutdown: (dry wt. equiv.)

a. Recycle belt
420 lb/min x min/180 ft x 200 ft = 460 lb

b. Other*
1800 lb - 460 lb = 1380 lb
(volume = 1380 lb x ft^3/1.6 lb = 840 ft^3)

* All or part of this may be included in the reject foam storage area.

-- Foam reject storage (assume 4-hour capacity)

500 lb/hr x ft^3/1.6 lb x 4 hr = 1220 ft^3
(dry wt. equiv.)

-- Liquid storage

Stage I water tank battery = 80,000 gal.
9900 gal./hr

Stage II oil/water
16,000 gal./hr

Protected Waters System

The performance requirements for this system include operation in 6-knot currents, two-foot waves and 20 mph winds; an oil recovery rate (minimum) of 1350 gal/hr net oil, with a desired rate of 2700 gal./hr.

All of the sorbent handling equipment modules of the offshore system may be applied directly to this situation. All components, as sized in the preceding section, have capacities in excess of these requirements. Longer booms are needed, since a foam-on-oil residence time of 60 seconds would require slightly more than 600 feet. It is likely that somewhat shorter residence times would be acceptable in this application, since excess foam and liquid handling capacities are available. Very few experimental data were obtained for times less than 60 seconds during this investigation, however.

The significant problem in operating any system in high currents is the deployment of the boom. It has been demonstrated that almost any boom will "fail" when the water velocity component normal to the boom exceeds 1.2 to 1.5 ft/sec. Higher current velocities will require deployment as a diversionary boom, maintaining a shape that does not permit the normal velocity component to approach failure. Deployment as a catenary (or parabola) might be assumed. Control of the boom angle at the downstream end would be by the tension in the boom. Boom design was not investigated, but recent in-house studies have shown that a diversionary boom having a 3-foot draft, when deployed in a 3.5-knot current so as to sweep only a 50-foot width, would require about 12,000 lb of tension to maintain the proper downstream angle. This would indicate that an oil spill from a concentrated source could be diverted toward a recovery system as shown in Figure 97. Note that the recovery, using sorbent in a contained area,

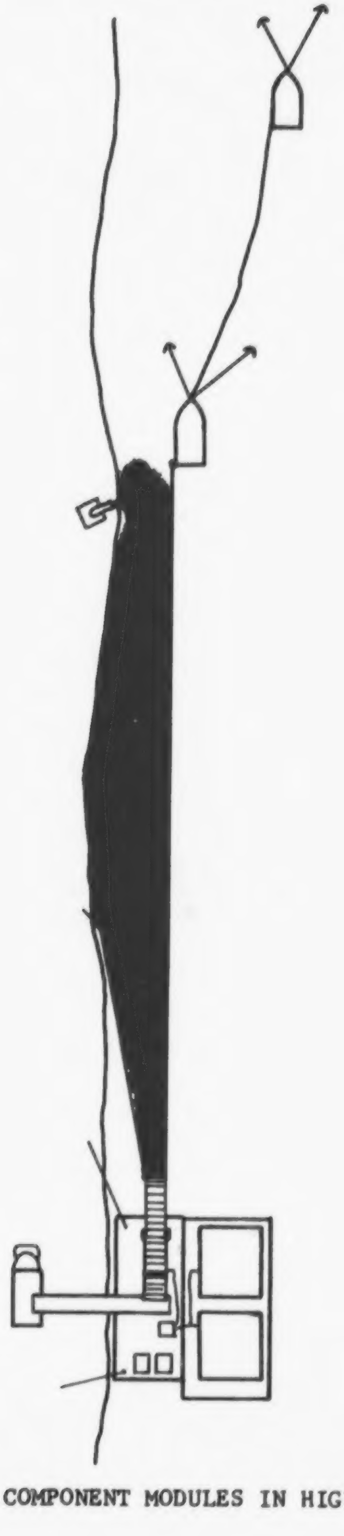


FIGURE 97 - USE OF COMPONENT MODULES IN HIGH CURRENT (RIVER)

requires only a very narrow channel when the current velocity is high (the specified 2700 gal/hr spill, when diverted so as to enter the recovery channel at a thickness of 0.06 in. would be only two feet in width).

The operation of the system in the manner shown in the Figure 97 is little different from the offshore situation. The component booms and vessels might be moored (note that the boom tension alone, in even the 3.5-knot current mentioned above, equates to approximately 500 horsepower), the harvester could be operated at a much smaller angle of inclination, and the recycling conveyor would be used to deliver foam to small barges (or trucks) for return to the distribution point.

Equipment Notes

General

Only limited consideration has been given in this investigation to specific or detailed equipment design. The concepts and the experimental units presented appear to be practical and capable of execution by experienced designers and fabricators of similar machinery; no new technology is involved, although some further experimental work is indicated in connection with the detailed design, such as eliminating or reducing the risk of explosion in the pneumatic conveying system by grounding and by safety panels, etc.

Power Supply

Wherever possible, the use of hydraulic drives, powered from packaged engine-driven power units, is recommended. This approach provides flexibility, redundancy, preserves the modular concept, and reduces or eliminates dependence upon shipboard supplies.

Component Modules

All system components have been described in a modular concept. Each module is suited to movement over the highway, although the pressurized penumatic conveyor must be palletized (its normal condition for storage and transport). Module and pallet size have been discussed briefly in this report. It appears that only certain modules will require disassembly for shipment by air (other than the palletizing already mentioned). These might be the longer belt conveyors and the pressurized pneumatic system storage hoppers. Disassembly would not be necessary for a C-130 type aircraft but would be required for side door loading in the more commonly-available Boeing 727 QC type aircraft.

Discussions with aircraft companies, cargo carriers, and reference to the AIR CARGO GUIDE (published by Reuben H. Donnelley) have established the following suggested limitations:

C-130 Hercules
Cargo compartment: 10 ft x 10 ft x 40*ft
Approximate payload cargo: 20,000 lbs

*Loading: Rear ramp, full compartment length is practical.

Boeing 727 - QC
Cargo compartment: 10 ft x 6 ft (curved overhead) x 19*ft
Approximate payload-cargo: 35,000 lbs

*Loading: side cargo door entry limits package length, depending on package height and width; the maximum length is 230 inches, if height is less than six feet with a width less than two feet.

Douglas DC-8
(Stretched version in cargo service)
Cargo compartment: 10 ft x 6-1/2 ft x 126*ft
Approximate payload: 80,000 lbs

*Loading: side door with restrictions on length similar to 727, but depends on particular airframe configuration.

All carriers contacted will accept palletized packages up to 10 ft x 7 ft x 4 ft ± high. Heights to six feet are possible, depending upon shape of package.

SECTION XV

ACKNOWLEDGMENTS

Key personnel who were responsible for this study:

R. A. Cochran - Wringer
D. P. Hemphill - Distribution; Harvesting; System Design
J. P. Oxenham - Sorption; Sorbent Collection
P. R. Scott - Foam Development; Sorbent Disposal
J. P. Fraser - Project Coordination

The Pipeline Research and Development Laboratory is directed by E. A. Milz

This project was supported by the Office of Research Monitoring of the Environmental Protection Agency. Mr. J. S. Dorrler was Project Officer.

SECTION XVI

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SECTION XVII

NOMENCLATURE

d = apparent foam thickness

d_s = depth of slick

D = foam concentration, lb/ft^2

G = dimensional constant

G' = dimensional constant

K = permeability of the sorbent

ΔM = total mass recovered

N - number of passes through the wringer

P = weight of roller

q = oil flux

Q = volume of oil

Q_∞ = volume of oil permanently retained in the foam

Q_o = initial oil volume

$\dot{Q}$ = total oil absorption rate (volume flow rate)

$\hat{Q} = \dfrac{Q}{\pi r_e^2}$

Q' = equivalent dry weight of foam recovered per hour per unit width of system

Subscripts:

C = in current
H = on harvester
F = on wringer feed
R = recycle

r = local radius

r_e = circular equivalent radius

r_i = local radius to edge of sorbent block

SPG = specific gravity of oil

t = time

$\hat{t} = \left(\dfrac{\Delta\sigma \, d_s \, K \Sigma_e}{\phi r_e^2} \right) t$

Δv = total volume recovered

V_B = belt speed

V_S = system speed

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w = width of belt

$\overline{W}$ = swept width

μ = oil viscosity

$\Delta\sigma$ = interfacial driving force

Σ_e = effective specific surface

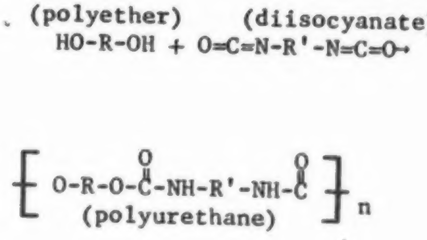
ϕ = porosity of the sorbent material

SECTION XVIII

APPENDIX 1

POLYURETHANE FOAM REACTIONS

There are numerous methods for the preparation of polyurethanes. The most widely used is the reaction of di or polyfunctional hydroxyl compounds with di or polyfunctional isocyanates. Linear polyurethanes are produced when difunctional polyethers or polyesters react with diisocyanates as shown below.

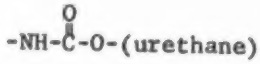


$$\underset{\text{(polyether)}}{\text{HO-R-OH}} + \underset{\text{(diisocyanate)}}{\text{O=C=N-R'-N=C=O}} \rightarrow$$

$$\left[\text{O-R-O-}\overset{\text{O}}{\overset{\|}{\text{C}}}\text{-NH-R'-NH-}\overset{\text{O}}{\overset{\|}{\text{C}}} \right]_n$$

(polyurethane)

The linkage



$$\text{-NH-}\overset{\text{O}}{\overset{\|}{\text{C}}}\text{-O-}\text{(urethane)}$$

characterizes polyurethanes although other groups, such as ether, ester, biuret, allophanate, amide, and other groups may be present in the polymer molecule.

Crosslinked polyurethanes are formed if the functionality of the hydroxyl or isocyanate component is increased to three or more.

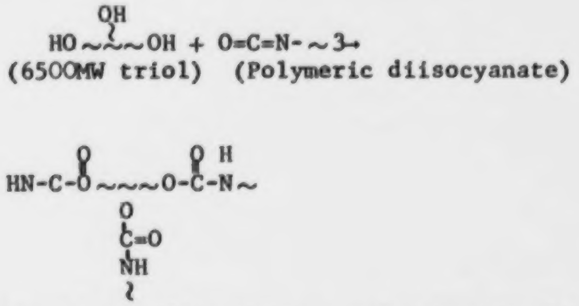
The properties of the various types of urethane polymers depend largely upon molecular weight and degree of crosslinking. Urethanes are versatile polymers. They include fibers, elastomers, adhesives, thermoplastics, thermosetting plastics, rigid foams, and flexible foams. The latter are of interest for sorbing oil spills. Open cell, low density polyurethane foams have been evaluated as oil sorbents by other researchers and have been used in the field for removing spilled oil.

The production of polyurethane foam at the site of an oil spill is desirable for several reasons. The development of the proper formulation to produce good quality foam in the varied ambient conditions existing at oil spills has been time consuming.

The open cell flexible polyurethane currently being used is made using the following components:

(1) Trifunctional polymeric polyol
(2) Polymeric methylene diphenyldiisocyanate
(3) Methylene chloride and
(4) Trimethylaminoethylpiperazine

The two most important reactions are those between the diisocyanate and trifunctional polyol (the chain propagating reaction) and between the diisocyanate and water (the foaming reaction). The characteristic urethane linkage is formed by the first reaction



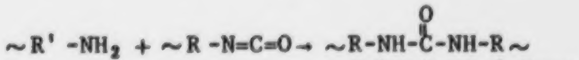
(6500MW triol) (Polymeric diisocyanate)

The reaction between the diisocyanate and water results in the liberation of carbon dioxide with simultaneous formation of an amine.

Diisocyanate Water Amine Carbon Dioxide

$$\sim R\text{-}N{=}C{=}O + H_2O \rightarrow \sim R'\text{-}NH_2 + CO_2\uparrow$$

The amine immediately reacts with additional isocyanate to form a substituted urea.



$$\sim R'\text{-}NH_2 + \sim R\text{-}N{=}C{=}O \rightarrow \sim R\text{-}NH\text{-}\overset{O}{\overset{\|}{C}}\text{-}NH\text{-}R\sim$$

Substituted Urea

Other reactions also occur which may cause crosslinking, chain propagation, etc. but for this purpose are considered minor.

The methylene chloride is added as an auxiliary blowing agent. The density of a flexible foam can be progressively lowered by increasing the diisocyanate and water levels, but this changes the polymer structure of the foam. An auxiliary blowing agent is added to decrease density without increasing crosslinking. The above reactions are exothermic. Sufficient heat is liberated to vaporize the methylene chloride. Increasing the auxiliary blowing agent decreases both the density and load bearing ability of the foam.

The above primary reactions are too slow for the production of urethane foams for practical purposes. The catalyst trimethylaminoethylpiperazine is employed to bring about faster rates of reactions. This catalyst not only brings about faster rates of reaction but also establishes a proper balance between the chain-propagating reaction (primarily the hydroxyl-diisocyanate reaction) and foaming reaction (diisocyanate-water reaction). A balance has to be established between the polymer growth and gas and vapor formation (1) prevent the development of sufficient strength in the cell walls to entrap large quantities of gas (2) develop sufficient polymer strength to prevent the collapse of the structure when the gas escapes the ruptured cells. When the chain extension and crosslinking reactions are predominant, the number of closed cell faces becomes greater and the porosity decreases. When the foaming reactions predominate, the foam collapses upon release of the gas and vapors. Tertiary amines catalyze both the isocyanate-hydroxyl and isocyanate-water reactions. However, all tertiary amines are not good catalyst. The efficiency of the tertiary amine generally increases as the basicity increases and as the steric shielding of the amino nitrogen decreases.

When the above components are intimately blended, a number of reactions take place very rapidly. A polymer is formed and expands to a density of one to three lb/ft^3 in about 45 seconds at 77^oF. The timing of the polymerization and expansion are critical and are controlled by the catalyst and the relative concentrations of the diisocyanate and water. The relative quantitites of components are usually critical; however, usable foam is produced when the quantity of any component in this recipe is varied about ±20%.

APPENDIX 2

POLYURETHANE FOAM FOR ABSORBING SPILLED OIL

The laboratory has tested numerous formulations for making flexible, open cell polyurethane foam.

The following polyurethane foam formulation produces 1.5 to 3 pounds per cubic foot density foam when made in beaker quantities in the laboratory, poured utilizing the laboratory portable foam equipment and when poured utilizing a commercial foam machine.

Component A	Parts
Jefferson Chemical Company Thanol SF 6500	100
Dichloromethane (Dow)	10
Water	5
Jefferson Chemical Company Thancat TAP	2
Component B*	
Rubinate-M (Jefferson Thanate P-30)	50-80

---

* Quantity of Component B depends upon ambient temperature, humidity, etc.

The material cost is about $0.37 per pound when drum lots of chemicals are purchased.

The ratio of Component A to Component B is not very critical; however, the ratio needs to be varied to form the best foam at the existing ambient condition. Good quality foams have been made at ambient temperatures from 40 to 120°F and relative humidities of from about 20 to 95%.

The following tests were designed to simulate conditions that may exist at an oil spill site.

1. Foam was made by pouring the mixed foam components directly on both wet and dry sand. The foam quality was good.
2. The mixed components were poured on newsprint paper. The foam quality was good.
3. The mixed components were poured on Teflon repeatedly to simulate a moving belt operation (see Figure 17). The foam

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quality was excellent and the foam removed one minute after pouring had 80 to 90% open cells at the foam-Teflon interface. Before the rise was complete another Teflon sheet was placed on top to simulate foam formed between two moving Teflon belts. Open cell structure was found at both interfaces. This operation simulates a more elaborate but practical technique. The moving belt concept would allow one to produce long thin strips of polyurethane with open cells on both sides. The long strips, 4-feet to 1000-feet or more could be applied to large or thick spills. The harvesting would be simplified.

4. The foam components were mixed and then applied directly to water surfaces. Reasonable quality foams were produced at times. The quantity of isocyanate and the stage of reaction before contact with the water are both critical. With practice, reasonable quality foam with open cells on the water interface side can be made.

5. The foam components after mixing were applied directly to oil floating on water surfaces. The above statements concerning success and application to water apply.

Additional batches of polyurethane foam components were made and evaluated during this study. Batches were made using Freon-11 as an auxiliary blowing agent, and batches were made to evaluate catalysts listed below:

1. Thancat® DD, Jefferson Chemical Company, Incorporated
2. Dabco®, Houdry Process and Chemical Company
3. T-9, M & T Chemicals, Incorporated
4. T-12, M & T Chemicals, Incorporated

Thancat DD® and Dabco® are tertiary amines, T-9 is stannous octoate, and T-12 is dibutyltin dilaurate.

Results of our tests with different catalysts are summarized below:

1. Thancat DD® and Thancat TAPwere found to be interchangeable. About 25%w less DD is required in otherwise comparable blends.

2. Tin catalysts were not satisfactory because (a) the tin catalysts lost activity when blended with water, (b) the quality of foam produced was very sensitive to the quantity of tin catalysts used. Tin catalysts are not recommended since it appears they would have to be injected as a carefully-metered separate component.

3. Dabco® is not recommended for use with Thanol SF-6500 MW Polyol and Polymeric MDI. The reactions catalyzed by this catalyst were not balanced. The reactions were too slow when a small

quantity of catalyst was used. When sufficient catalyst was used to produce a tack-free foam in five minutes, the foaming reaction (CO_2 liberation) exceeded the crosslinking reaction to such an extent the resulting foam slumped.

No foam formulation tested was better than the original available at the beginning of testing. However, we gained considerable experience in the production of polyurethane foam and knowledge concerning the flexibility of operation which is available to us in the use of polyurethane foam for oil sorption.

The foam formulation described below produced a good foam for absorbing oil. However, there are insufficient closed cells to give it good buoyancy after water wetting.

Component	Parts
Thanol SF-6500	100
Freon-11	10
Water	6
Thancat DD®	1.5
Rubinate M	60

A 100-pound quantity of foam was made from this formulation using our foam machine. The Thanol, Freon-11, water, and Thancat were blended to make one component (B component). This B component was then mixed with the isocyanate (A component) with a Binks 18 FM gun. The ratio of A to B was 1:2 by weight. The resulting 1.75 lb/ft^3 foam had a rise time of one minute and was tack-free in 1-1/2 minutes. This foam has tear and compression characteristics which make it an excellent foam for spreading with the hay spreader but at the cost of greater attrition during recycling.

APPENDIX 3

TOXICITY TESTS OF POLYURETHANE FOAM GENERATED ON SITE

One concern with the use of on-site generated polyurethane foam as an oil sorbent is the ecological damage which might be caused by the foam, due to the leaching of unreacted components from the foam into the water. To test this possibility, the Edna Wood Laboratories, Houston, Texas have made 96-hour acute toxicity tests using F. Similis, a small seawater fish. Results are shown in the attached report. Fish ate the foam with no apparent ill effects. These bioassays are considered to be a more sensitive measure of possible leaching effects than any chemical analyses we could make. The foam used in these tests is described in Table 9.

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Fish Sizes:
Largest - 4.6 grams - 65mm
Average - 3.7 grams - 61mm
Smallest - 34. grams - 58mm

96 Hr. TLm - Apparently not toxic

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4820 Old Spanish Trail Houston, Texas 77021

Bioassay Work Sheet
Physiological Observations

Shell Pipeline
Bioassay No. ______

E. similis
species fish used
5 Fish/10 l

Sample Marked Polyurethane Foam

Received 13 Jan 1972

Sample Concentrations, ppm ~~% by volume~~

	10		100		500		1000		2000	
	6_1	6_2	7_1	7_2	8_1	8_2	9_1	9_2	10_1	10_2
17 Jan 1972 1220										
18 Jan 1972 1230	Norm.	Norm.	Norm.	Norm.	Norm.	Norm.	Norm.	Norm.	Norm.	Norm.
19 Jan 1972 1300	-	-	-	-	-	-	-	-	-	-
20 Jan 1972 1230	-	-	-	-	-	-	-	-	-	-
21 Jan 1972 1220	-	-	-	-	-	-	-	-	-	-
	All control fish normal at the end of 96 hours									
Note: The fish bit at the foam as tho it were food, but spit it out apparently now swallowing any.										

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4820 Old Spanish Trail Houston, Texas 77021

Shell Pipeline
Bioassay No. ________

Bioassay Work Sheet
Physio-Chemical Observations

Date & Time	Test Tank	Polarograph µ amps	Polarograph O_2 mg/l	pH	Sp. Res. ohms	Temp. °C	
17 Jan 1972 1225	6_1	>10	>13.5	7.8	60	19	
	6_2	✓	✓	7.8	60	✓	
	7_1	✓	✓	7.82	60	✓	
	7_2	✓	✓	7.82	60	✓	
	8_1	✓	✓	7.88	60	✓	
	8_2	✓	✓	7.88	60	✓	
	9_1	✓	✓	7.88	60	✓	
	9_2	✓	✓	7.88	60	✓	
	10_1	✓	✓	7.9	60	✓	
	10_2	✓	✓	7.98	60	✓	
	C	✓	✓	7.9	60	✓	
	C	✓	✓	7.9	60	✓	

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Bioassay No. P92

Bioassay Work Sheet
Physio-Chemical Observations

Date & Time	Test Tank	Polarograph		pH	Sp. Res. ohms	Temp. °C	
		μ amps	O_2 mg/l				
18 Jan 1972 1240	6_1	>10	>13.5	7.02	54	20	
	6_2	-	-	7.1	-	-	
	7_1	-	-	7.25	-	-	
	7_2	-	-	7.22	-	-	
	8_1	-	-	7.2	-	-	
	8_2	-	-	7.2	-	-	
	9_1	-	-	7.2	-	-	
	9_2	-	-	7.15	-	-	
	10_1	-	-	7.3	-	-	
	10_2	-	-	7.1	-	-	
	c	-	-	7.08	56	-	
	c	-	-	7.05	56	-	

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Bioassay No. ________

pg 3

Bioassay Work Sheet
Physio-Chemical Observations

Date & Time	Test Tank	Polarograph		pH	Sp. Res. ohms	Temp. °C	
		µ amps	O_2 mg/l				
19 Jan 1972 1400	6_1	>10	>13.5	6.82	54	20	
	6_2	-	-	6.9	-	-	
	7_1	-	-	7.02	-	-	
	7_2	-	-	7.0	-	-	
	8_1	-	-	6.9	-	-	
	8_2	-	-	7.0	-	-	
	9_1	-	-	6.9	-	-	
	9_2	-	-	6.9	-	-	
	10_1	-	-	7.0	-	-	
	10_2	-	-	6.9	-	-	
	c	-	-	6.9	55	-	
	c	-	-	6.9	55	-	

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Bioassay No. P94

Bioassay Work Sheet
Physio-Chemical Observations

Date & Time	Test Tank	Polarograph		pH	Sp. Res. ohms	Temp. °C	
		μ amps	O_2 mg/l				
20 Jan 1972 1230	6_1	>10	>13.5	7.3	54	20	
	6_2	-	-	7.4	54	-	
	7_1	-	-	7.6	55	-	
	7_2	-	-	7.55	54	-	
	8_1	-	-	7.6	54	-	
	8_2	-	-	7.5	55	-	
	9_1	-	-	7.45	54	-	
	9_2	-	-	7.2	54	-	
	10_1	-	-	7.45	54	-	
	10_2	-	-	7.28	54	-	
	c	-	-	7.5	55	-	
	c	-	-	7.52	56	-	

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Bioassay No. P15

Bioassay Work Sheet
Physio-Chemical Observations

Date & Time	Test Tank	Polarograph μ amps	 O_2 mg/l	pH	Sp. Res. ohms	Temp. °C	
21 Jan 1972 1230	6_1	>10	>13.5	7.19	54	20	
	6_2	✓	✓	7.25	✓	✓	
	7_1	✓	✓	7.33	✓	✓	
	7_2	✓	✓	7.2	✓	✓	
	8_1	✓	✓	7.4	✓	✓	
	8_2	✓	✓	7.4	✓	✓	
	9_1	✓	✓	7.32	✓	✓	
	9_2	✓	✓	7.22	✓	✓	
	10_1	✓	✓	7.33	✓	✓	
	10_2	✓	✓	7.1	✓	✓	
	c	✓	✓	7.35	56	✓	
	c	✓	✓	7.4	56	✓	